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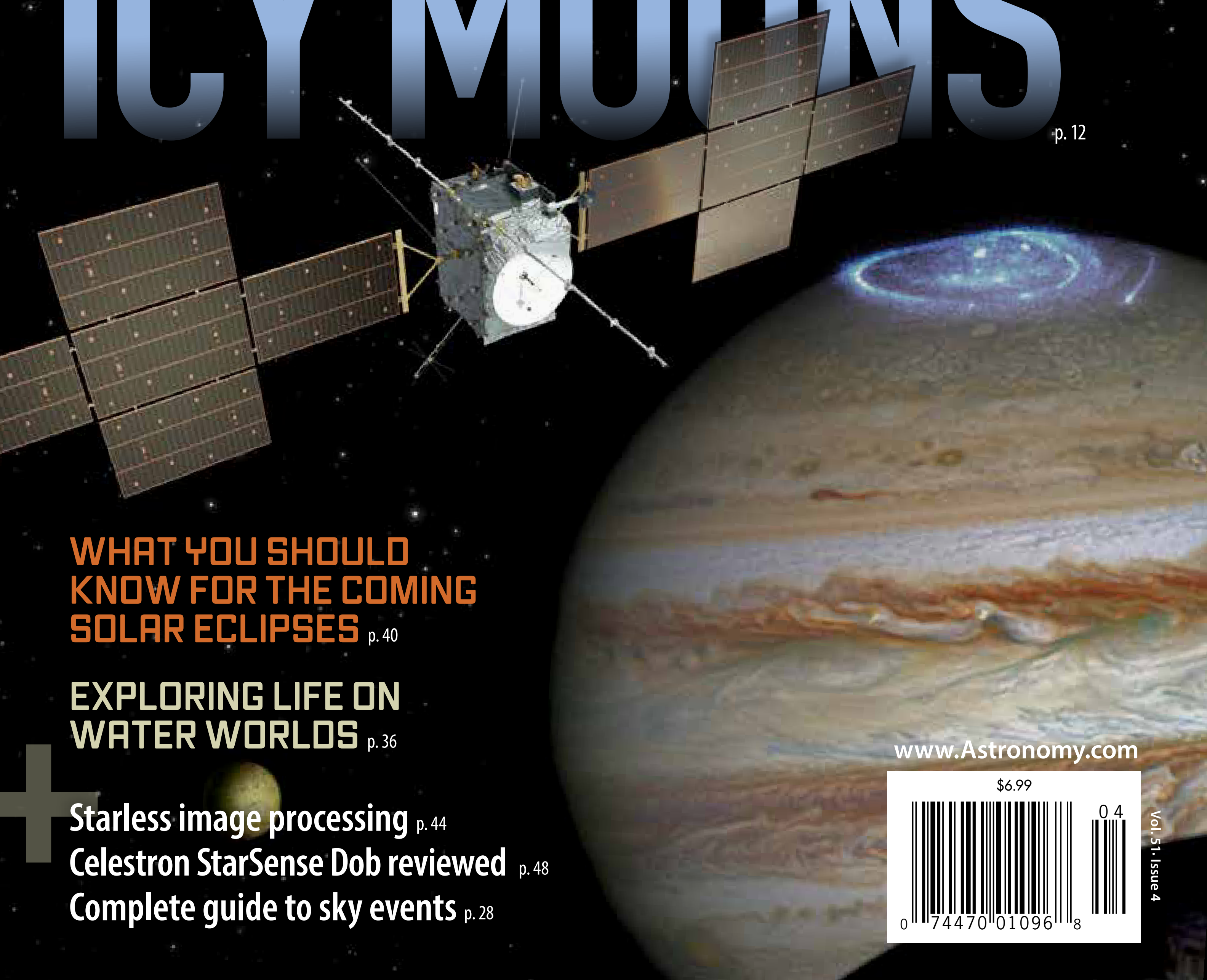

WHAT YOU SHOULD KNOW FOR THE COMING SOLAR ECLIPSES p. 40

EXPLORING LIFE ON WATER WORLDS p. 36

+

Starless image processing p. 44
Celestron StarSense Dob reviewed p. 48
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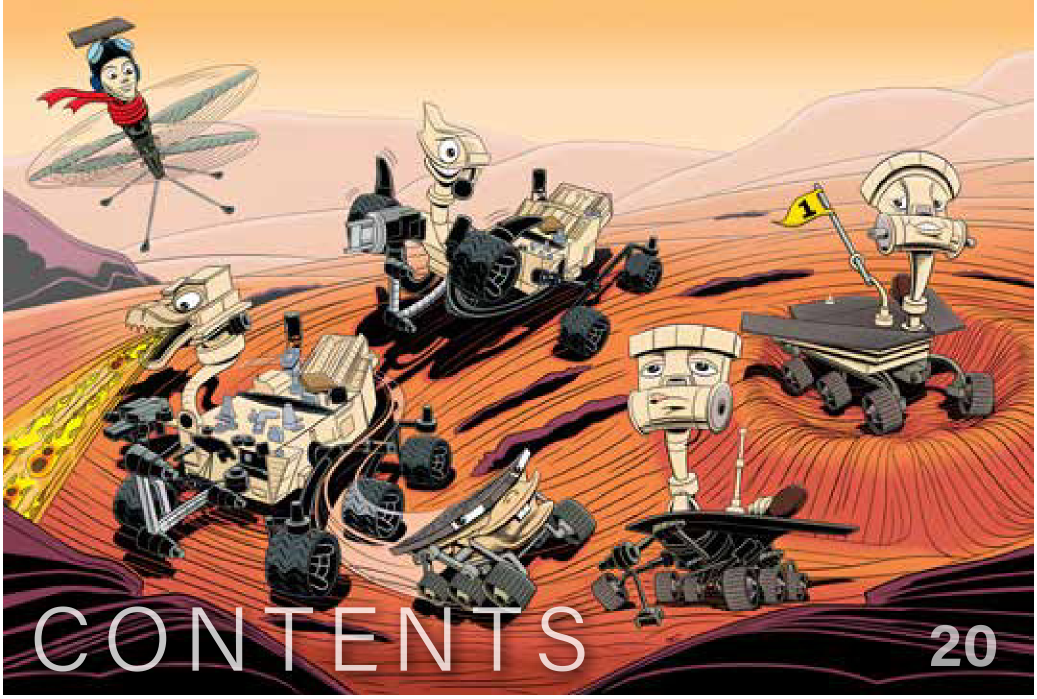


CONTENTS

FEATURES

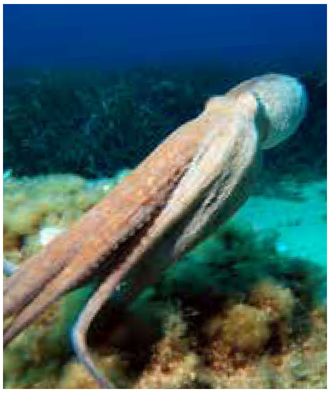
12 COVER STORY
Mission to Jupiter's icy moons
Europa, Ganymede, and Callisto harbor potential subsurface oceans. Soon, JUICE will show them as never before.
BEN EVANS

20
The many personalities of NASA's Mars rovers
The first explorers of Mars include the rich and entitled, the bratty kids, the barnstorming aviators, and the selfie-obsessed social media sensations. (Did you think we meant humans?)
MELISSA RICE

28
Sky This Month
A rare hybrid eclipse.
MARTIN RATCLIFFE AND ALISTER LING

30
Star Dome and Paths of the Planets
RICHARD TALCOTT; ILLUSTRATIONS BY ROEN KELLY

36
Searching for life on watery worlds
Life within extraterrestrial oceans may not only be possible, it might be flourishing.
KLAUS R. BRASCH



40
Upcoming eclipses by the numbers
In the next 12 months, an annular and then a total solar eclipse will cross the U.S. Here's where to see them.
MICHAEL ZEILER

44
Erasing stars with AI tools
Change up your astroimaging routine with starless skyscapes.
WARREN KELLER

48
We test Celestron's 10-inch StarSense Explorer
This scope uses your smartphone to put thousands of deep-sky objects at your fingertips. **MICHAEL E. BAKICH**

54
Ask Astro
Warp speed.

»

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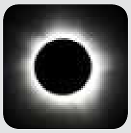

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ESA's JUICE mission will shed light on Jupiter's largest satellites.

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COLUMNS

Strange Universe **11**
BOB BERMAN

Secret Sky **50**
STEPHEN JAMES O'MEARA

Binocular Universe **52**
PHIL HARRINGTON

7
QUANTUM GRAVITY
Everything you need to know about the universe this month: A young galaxy plays peekaboo, a GRB defies expectations, and a newborn star grows — plus much more.

IN EVERY ISSUE

From the Editor **4**
Astro Letters **6**
New Products **53**
Advertiser Index **53**
Reader Gallery **56**
Breakthrough **58**

Astronomy (ISSN 0091-6358, USPS 531-350) is published monthly by Kalmbach Media Co., 21027 Crossroads Circle, P. O. Box 1612, Waukesha, WI 53187–1612. Periodicals postage paid at Waukesha, WI, and additional offices. POSTMASTER: Send address changes to *Astronomy*, PO Box 8520, Big Sandy, TX 75755. Canada Publication Mail Agreement #40010760.

FROM THE EDITOR

Looking for life

JUICE launches this month atop an Ariane 5 rocket, poised to explore moons of Jupiter that could harbor tiny life. ESA/CNES/ARIANESPACE-SERVICE OPTIQUE CSG

This month, an exciting mission takes off from the launchpad. The JUpiter Icy Moons Explorer, better known as JUICE, heads for an encounter with our largest planet's satellites, beginning with its arrival in the jovian system in 2031.

With all of our hopes, dreams, aspirations, and wonder about life elsewhere in the cosmos, it's possible that life exists right here in other places in our solar system. JUICE will explore three of Jupiter's moons — Ganymede, Callisto, and Europa — all of which have subsurface oceans that hypothetically could host microbial or even somewhat more complex life. Our frequent contributor, British space journalist Ben Evans, a provides a detailed look at JUICE beginning on page 12. The eight-year journey to jovian worlds will give us lots of time to contemplate the possibilities.

We don't know exactly how the first organic molecules evolved into self-replicating systems on Earth, but the knowledge base of how lipids, cellular walls, RNA, and DNA got going is deepening year by year. And organic chemistry is the answer. As my friend Richard Dawkins likes to say, life doesn't need to be "magicked" into existence. Reflecting on JUICE and on possibilities for microbial life in other outer solar system moons, Arizona-based writer Klaus Brasch delivers a related story on page 36, surveying the solar system's water worlds.

I hope you'll enjoy thinking about the origins of life, and the long journey ahead for JUICE during the coming days and weeks. Perhaps we are even on the cusp of learning more about how we earthlings are not alone in the very big cosmos.

Yours truly,

David J. Eicher
Editor

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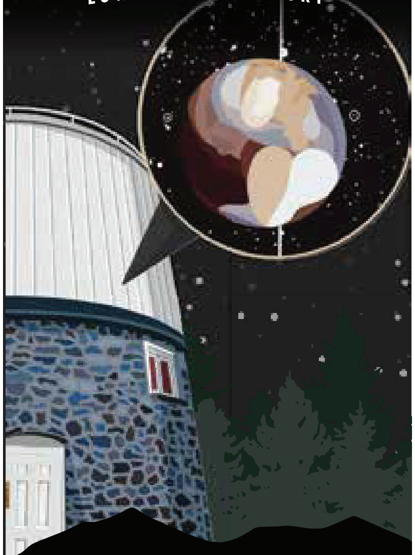

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Exploration versus colonization

Seth Shostak's article on photographing the worlds of our solar system ("Oh the spaces we'll go," October 2022) is all very nice, except human travel to these places will not be funded for the sake of photography. Many wishful thinkers tend to confuse the 15th and 16th centuries' Age of Exploration, which was funded to seek riches and to acquire and exploit land for colonization, with this century's exploration of the solar system, which will never be funded for those reasons. Also, technology already provides superb photography of the solar system, and robotic systems can certainly be improved to remotely add the artistic touch to photography. — **Christopher Jekeli,** Brunswick, ME

Feeling small

STRANGE UNIVERSE

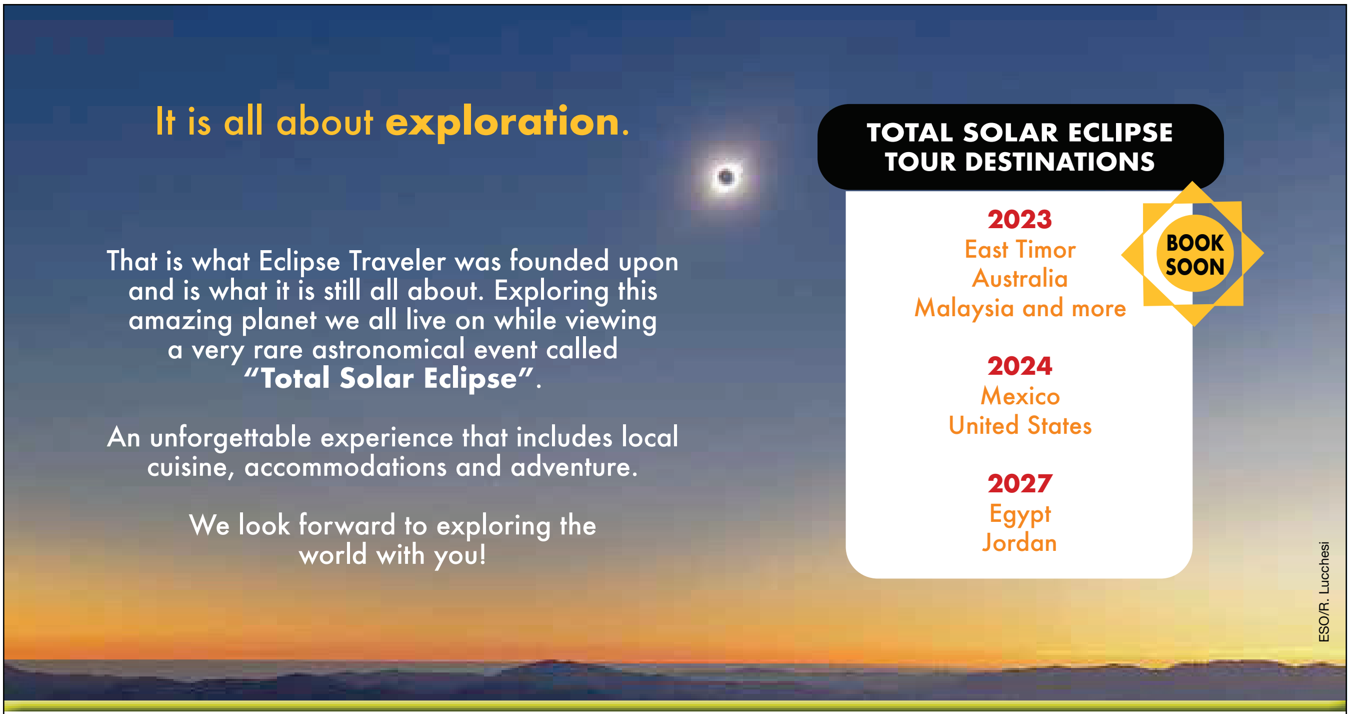
Galaxy-sized ego

Astronomy can inflate your sense of self-worth — or diminish it.

The concept of ego that Bob Berman discusses in his November 2022 column is indeed interesting. In general, one feels very small thinking about the stars. However, someone once asked an astronomer if the pursuit didn't indeed make one feel insignificant, to which he replied: "Not at all, I also have a microscope." — **James Fradgley,** Wimborne Market, England

A book's influence

How can you leave Ptolemy's *Almagest* off your list of top 10 astronomy books of all time (December 2022)? The geocentric model of *The Almagest* was incorrect, but the predictions it made of the positions of objects in the night sky were so good that they were used to prepare astronomical charts from A.D. 150 to the early 17th century. — **Michael Bertin,** Irvine, CA



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Astronomy

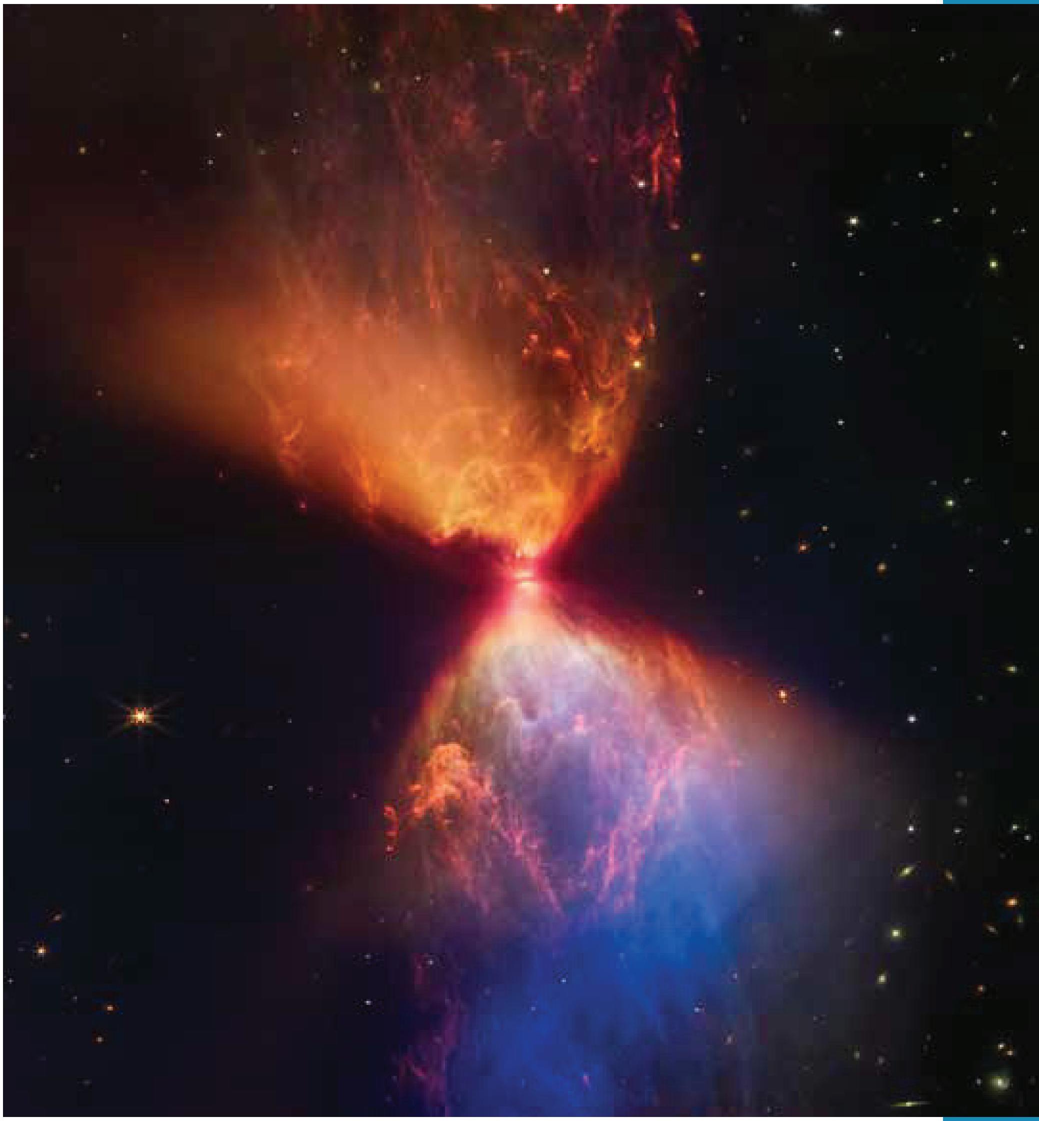
QUANTUM GRAVITY

EVERYTHING YOU NEED TO KNOW ABOUT THE UNIVERSE THIS MONTH

SNAPSHOT

A STAR IN THE MAKING

The Webb space telescope captures a blazing newborn star early in its development.



A stunning hourglass shape surrounds dark cloud L1527, located some 460 light-years away in Taurus and seen in one of the latest spectacular images taken by NASA's James Webb Space Telescope (JWST).

The view reveals giant clouds of material that are feeding the growth of a fledgling protostar located in the neck of the hourglass figure. The protostar itself remains hidden due to copious dust, but JWST's Near-Infrared Camera was able to reveal the surrounding region in incredible detail. Strings of gas and dust highlight cavities in the cloud carved out by the wind and radiation from the protostar within. Regions where the dust is thinnest appear blue, while thicker pockets take on an orange hue.

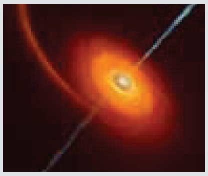
With images like these, astronomers not only get a deeper understanding of the wild region around L1527 specifically, but they also gain general insight into the formation of star systems like our own. —SAMANTHA HILL

SCIENCE: NASA, ESA, CSA, STSCI; IMAGE PROCESSING: JOSEPH DEPASQUALE (STSCI), ALYSSA PAGAN (STSCI), ANTON M. KOEKEMOER (STSCI). BOTTOM FROM LEFT: KOREA AEROSPACE RESEARCH INSTITUTE; ESO/M.KORNMESSER; NASA

» HOT BYTES

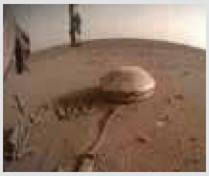
HIGH-WAY MILEAGE

After a 4.5-month journey, South Korea's first deep-space mission, Danuri, entered lunar orbit Dec. 16 using a ballistic lunar transfer. This fuel-efficient trajectory took it out to nearly the Earth-Sun L1 Lagrange point before it fell back to the Moon's vicinity.



RECORD GULP

A bright event detected in February 2020 was caused by a black hole swallowing a star, new research shows. Named AT2022cmc, it is the most distant known example of such an occurrence; its light traveled for about 8.5 billion years to reach us.

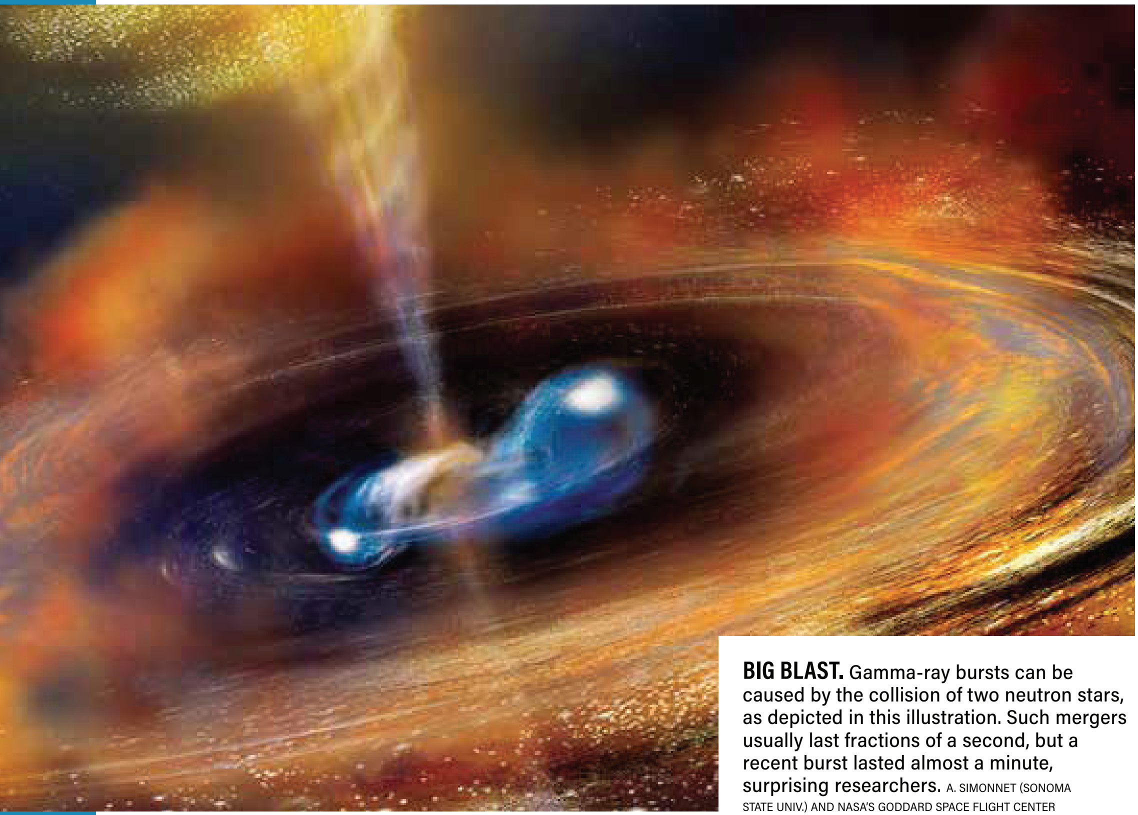


FAREWELL, INSIGHT

On Dec. 21, NASA said the Mars InSight lander had reached the end of its mission. The craft, which studied marsquakes and the planet's interior, ran out of power after dust coated its solar panels. Its last communication was Dec. 15.

HYBRID EXPLOSION UPENDS GAMMA-RAY SCIENCE

A recent gamma-ray burst defies categorization.



BIG BLAST. Gamma-ray bursts can be caused by the collision of two neutron stars, as depicted in this illustration. Such mergers usually last fractions of a second, but a recent burst lasted almost a minute, surprising researchers. A. SIMONNET (SONOMA STATE UNIV.) AND NASA'S GODDARD SPACE FLIGHT CENTER

» In 2021, a flash of high-energy gamma rays attracted the attention of both NASA's Neil Gehrels Swift Observatory and its Fermi Gamma-ray Space Telescope. Because gamma-ray bursts are both rare and short-lived — sometimes as brief as milliseconds — an automated alert shot out to telescopes around the world, inviting them to immediately scour the area for further signals. Telescopes from Hawaii to Spain turned their eyes to a spot in space a billion light-years away in the constellation Boötes. They collected data at multiple wavelengths, from X-rays to visible to infrared.

Together, the data told a shocking story. The event, known as GRB211211A, did not fit into either of the two neat categories astronomers usually use to sort gamma-ray bursts. Instead, it contained elements of both, and is now causing an upheaval in scientists' understanding of these powerful explosions.

BOTH SHORT AND LONG

Since the first gamma-ray burst was discovered in 1967, scientists have tried to puzzle out the mysteries of these events. For starters, they're astonishingly brief in astronomical terms. They give off extremely high-energy radiation, often while remaining invisible and undetectable at other wavelengths.

And up until now, they have always come in two distinct flavors: short and long. Short bursts last less than two seconds and are followed by a kilonova, an extremely bright explosion detectable at visible and infrared wavelengths. These events are thought to occur when two neutron stars, or a neutron star and a black hole, merge. Many have been found in the cosmic hinterlands, far away from busy galaxy centers.

Long bursts last, well, longer than two seconds. But even the longest are over in a matter of hours, more commonly minutes. Astronomers think long bursts occur when a massive star collapses into a black hole or neutron star in a supernova. Since massive stars have short lifespans, this means long bursts usually occur in crowded regions that are actively forming stars.

Because of their here-and-gone nature, gamma-ray bursts are difficult to study, and astronomers know there are gaps in their knowledge. There had been hints that gamma-ray bursts might not be as neatly divided as astronomers thought, but those observations were muddled by uncertainty: Were some events nearby and normal, or were the details simply obscured by distance or dust? The data were unclear.

GRB211211A is the first gamma-ray burst known to clearly double-dip the two categories. It was a long burst, lasting 51 seconds, but astronomers also observed bright optical and infrared light at the same location, indicating a kilonova. This upends decades of astronomical theory and observations, which had so far understood short and long gamma-ray bursts to be distinct events arising from different phenomena.

SOMETHING NEW

So, what kind of cosmic

occurrence could give rise to this hybrid event? Scientists don't yet agree on the details, but they do agree that the event was almost certainly a merger and not the collapse of a massive star. That would make GRB211211A a "short" gamma-ray burst of exceptional length.

Because gamma-ray bursts appear unexpectedly, the field takes an all-hands-on-deck approach to gathering information. NASA texted an alert as soon as the burst happened, and telescopes and observing teams around the world followed up, each group analyzing the data independently. In December, scientists published four papers simultaneously in *Nature*, along with a fifth in *Nature Astronomy*, to announce their findings.

The groups agree that a merger scenario best explains the evidence, but what is merging remains uncertain. One group, led by Jun Yang of Nanjing University, suggests a white dwarf and neutron star, while a team led by Eleonora Troja of the University of Rome Tor Vergata suggests two neutron stars. One thing the groups agree on is that the event opens a new chapter of gamma-ray-burst science, as the seemingly impossible just became reality. —KOREY HAYNES

Peekaboo! A young galaxy emerges

THIS FAINT DWARF GALAXY, which measures just 1,200 light-years across, has the official name HIPASS J1131–31. But because it only emerged from behind a fast-moving foreground star in the past 50 to 100 years, astronomers have given it the nickname Peekaboo. An analysis published Nov. 12 in *Monthly Notices of the Royal Astronomical Society* found that it severely lacks elements heavier than helium, or what astronomers call metals.

This trait is usually seen only in young galaxies in the distant, early universe. But the Hubble Space Telescope managed to resolve about 60 stars in Peekaboo, allowing astronomers to pin its distance at just around 22 million light-years. Spectroscopic data captured by the Southern African Large Telescope (SALT) indicates the tiny galaxy's stars only started forming in the last billion years or so, which would make it one of the youngest galaxies in our cosmic neighborhood yet found.

LATE ARRIVAL. The Peekaboo Galaxy (right of center) only emerged from the glare of the Milky Way star TYC 7215-199-1 in the past 100 years.

SCIENCE: NASA, ESA, IGOR KARACHENTSEV (SAO RAS); IMAGE PROCESSING: ALYSSA PAGAN (STSCI)

"At first we did not realize how special this little galaxy is," said study co-author Bärbel Koribalski, an astronomer at the Australia Telescope National Facility, in a NASA news release. With the new data, "we know that the Peekaboo Galaxy is one of the most metal-poor galaxies ever detected."

Co-author Gagandeep Anand of the Space Telescope Science Institute in Baltimore said: "Uncovering the Peekaboo Galaxy is like discovering a direct window into the past, allowing us to study its extreme environment and stars at a level of detail that is inaccessible in the distant, early universe."

The team hopes to obtain further observations with Hubble and the James Webb Space Telescope to learn more about Peekaboo's stars. "Due to Peekaboo's proximity to us, we can conduct detailed observations, opening up possibilities of seeing an environment resembling the early universe in unprecedented detail," Anand said. —JAKE PARKS

QUICK TAKES

DARK-SKY THREAT

In November, the International Astronomical Union expressed concern about a prototype satellite called BlueWalker 3, launched Sept. 10 by AST SpaceMobile. Its nearly 700-square-foot (64 square meters) antenna can appear as bright as a magnitude 1 star.

EERIE GLOW

Data from the Hubble Space Telescope has revealed a steady background glow that permeates the solar system, distinct from the zodiacal light of dust in the ecliptic plane. It may be due to additional dust from comets that approach the Sun from all directions.

VOLCANIC DISRUPTION

An eruption that began Nov. 27 on Hawaii's Mauna Loa — the volcano's first in 38 years — halted operations of a solar telescope and the atmospheric station that has tracked the rise of carbon dioxide since 1958 to produce the famed Keeling Curve.

ALL THAT GLITTERS

Stars with unusually high concentrations of gold — of which hundreds are known — are likely older than the Milky Way, says a study published Nov. 14. Supercomputer simulations found such stars formed in progenitor galaxies that eventually merged to form our galaxy.

GROUNDBREAKING WORK

Construction has begun on the Square Kilometre Array, a network of radio telescopes that will span South Africa and Australia. When completed in 2028, it will be the largest such array in the world.

REHEATED REGOLITH

Researchers have suggested a novel method of building landing pads for rockets on the Moon: blasting the ground with microwaves to sinter (or melt) soil particles into a solid mass. If the cost of transporting materials to the Moon remains high, it's cheaper than paving.

— MARK ZASTROW

Megatsunami swept across ancient Mars

DEBRIS FIELD. NASA's Viking 1 lander may have touched down on the site of a megatsunami. NASA

AROUND 3.4 BILLION YEARS AGO, when Mars was warmer and wetter, an asteroid a few miles wide tore through its air and crashed into a shallow ocean, leaving an expansive crater on the seafloor. The impact was a martian analogue to the famous Chicxulub impact off the Yucatán Peninsula: It sent a wave of water up to 820 feet (250 meters) high surging inland for hundreds of miles, leaving behind a layer of debris hundreds of feet thick.

Using satellite data and computer simulations to reconstruct the event, a team of researchers say they have identified the crater that the asteroid left behind: Pohl, 68 miles (110 kilometers) wide, lying on the plains of Chryse Planitia. The analysis was published Dec. 1 in the journal *Scientific Reports*.

Intriguingly, one spacecraft has already explored this catastrophe's aftermath. In 1976, the Viking 1 lander touched down some 560 miles (900 km) southwest of Pohl — right on top of the megatsunami deposit.

The new findings help explain the landscape Viking 1 found. Imagery from early Mars orbiters showed that the region is marked by massive channels, thought to be carved out during megafloods that sprung from underground aquifers and rushed downhill to fill a vast northern sea. But when Viking 1 landed, its immediate surroundings were flat and strewn with boulders, leaving researchers to wonder whether it had landed on a lava field. Scientists assumed Viking 1 had missed out on sampling rocks that had potentially been in contact with water — or any life that may have existed in that water.

But that wouldn't be the case if the boulders at the landing site were washed ashore by a megatsunami. "The deposit could have transported water that existed in habitable environments for hundreds of millions of years," study leader Alexis Rodriguez, a researcher at the Planetary Science Institute in Tucson, tells *Astronomy*. That could make the region and Pohl itself prime sites for further searches for ancient martian life. – M.Z.

COSMIC CLIFF DEEP DIVE

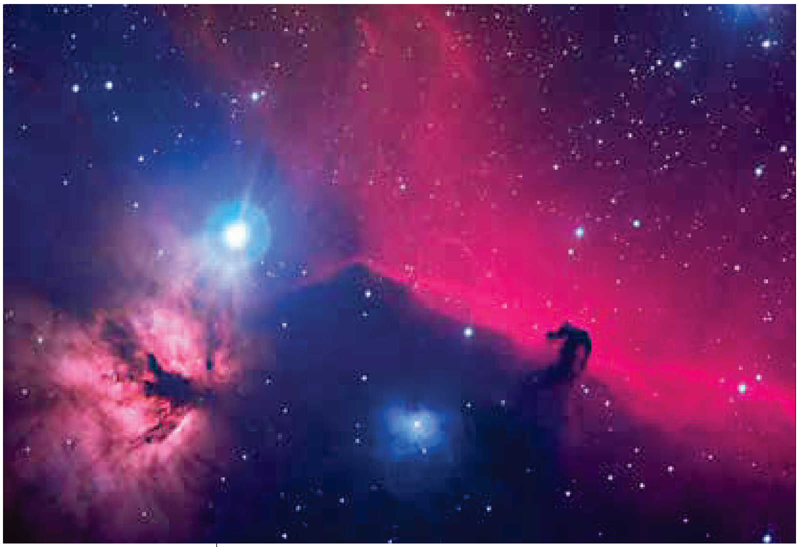
IMAGE: NASA, ESA, CSA, STSCI. SCIENCE: MEGAN REITER (RICE UNIVERSITY); IMAGE PROCESSING: JOSEPH DEPASQUALE (STSCI), ANTON M. KOEKEMOER (STSCI)

When NASA released the first science images from the James Webb Space Telescope (JWST) last July, one of the standouts was a region that scientists dubbed the Cosmic Cliffs, at the edge of the star cluster NGC 3324 in Carina roughly 7,600 light-years away. Although the area is known for spawning stars, its abundant gas clouds absorb much of their light at visible wavelengths. By homing in on data from JWST's Near-Infrared Camera at a wavelength of 4.7 microns, researchers permeated the puffs and found 24 outflows throughout the region from young stars spitting out molecular hydrogen in the form of jets. Such activity is key to understanding this period of a star's life, which lasts only a few thousand years and is not well documented. Researchers hope JWST will change that. – S.H.

STRANGE UNIVERSE

Danger and glory

Orion's Belt hides some blazing secrets.



Bright Alnitak (left of center) is bordered by the Flame Nebula (lower left) and the Horsehead Nebula (lower right). The star's blazing UV photons ionize the surrounding gas, making it glow.
DYLAN O'DONNELL

For once, let's not seek out the esoteric but do our exploring in one of the night's most familiar places: the belt of Orion. Its leftmost star, Alnitak (pronounced ALL-nye-tack), is our focus this month.

Alnitak is blue because it's hotter than most stars. And boy, is it *hot*, shining at visible wavelengths with the light of 10,000 Suns! Can any of us imagine what 10,000 Suns would be like? Most of its energy isn't even fiercely hot blue light, but instead deadly ultraviolet (UV), the stuff that punishes our beach vanity with a painful sunburn — except that Alnitak's UV is largely the intense UVC radiation. The miniature wavelengths from UVC ionize atoms and cause worrisome mutations, but Earth's ozone layer blocks them.

Alnitak is ultrabright, blue, and super hot.

The star is ultrabright, blue, and super hot because it consumes its fuel incredibly fast. Our Sun loses 4 million tons of itself per second, but Alnitak weighs 200 million tons less each second. That's because its core pressure is super high, and *that* is because the star is so heavy: Alnitak weighs as much as 28 times more than our Sun, which is the bottom-line explanation for the whole ferocious process.

Such heavy, blue, dazzling stars are classified as type O, and they're as rare as silent kindergartens. Only 1 star in every 3 million is an O-type star. But Orion has a few all by itself.

Although Alnitak is 20 times wider than the Sun and has dozens of times more mass, its feeding frenzy ensures it won't live long. Alnitak wasn't even around when Earth's first grasses appeared 55 million years ago. In less than a few million years more, it will have used up too much fuel and will expand, change color, and become a red supergiant like Betelgeuse. And it will detonate as a supernova soon thereafter.

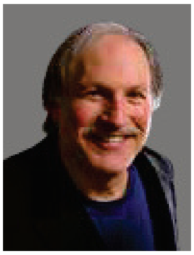
That will certainly change the look of Orion's Belt — a pattern of stars that has always been noticed. (It's mentioned in the Bible. And in movies like *Men in Black*.)

Zooming back in on Alnitak, the light that rushes out of this star is so energetic that the space around it is a very dangerous place. The Flame Nebula (NGC 2024) almost touches Alnitak's eastern side, and a narrow streak of glowing gas as long as two Full Moons dangles south of it, illuminated and excited by its UV photons. Halfway along that streak is the famous Horsehead Nebula (Barnard 33).

That celestial chess piece may be the most challenging telescope object of them all. I've never seen it in a half-century of observing, even with my dark skies and 12½-inch f/6 reflector. If, like me, you love cosmic challenges, you've probably observed the asteroid Vesta and the planet Uranus with just the naked eye. But the Horsehead? For most, it's a mythical object that, like love, can be spoken of but not seen. And it would never even be photographed, were it not for the background glow supplied by Alnitak's energy.

If you have dark conditions, notice all the little faint stars that richly surround Alnitak and the other belt stars. If it's a moonless rural night, your naked eye is enough to see this nameless star cluster I'm obsessed with mentioning once a decade. Point binoculars at the belt, and this odd grouping in which it's embedded becomes obvious and rich — even poetically inspiring, since Alnitak and its surrounding stars mark the closest nursery of copious star birth. They, and indeed most of Orion's stars, are associated with the Orion Nebula (M42) a few degrees lower — the fairyland that reliably thrills lovers of the heavens and which looks red, blue, and purple when photographed, but only green through the eyepiece.

Hot, blue Alnitak is some 800 light-years away. In our own neighborhood, most stars are a mellow yellow or cooler orange, and their radiation is manageable and life-friendly. So, while we have the luxury of enjoying Alnitak from afar, it would be a much different story if it were closer. And it just goes to show that the stupendous and strange can hide within one of the most familiar star patterns in the night sky.



BY BOB BERMAN
Bob's recent book, Earth-Shattering *(Little, Brown and Company, 2019), explores the greatest cataclysms that have shaken the universe.*

BROWSE THE "STRANGE UNIVERSE" ARCHIVE AT **www.Astronomy.com/Berman**

Mission to Jupiter's
ICY MOO

ESA's JUpiter ICy moons Explorer will shed light on the structure and history of our solar system's largest satellites, with a specific focus on the icy worlds Ganymede (foreground), Callisto (far upper right), and Europa (right of center). Also shown is Jupiter's volcanic moon, Io (lower left). The spacecraft, planet, and moons are not to scale. SPACECRAFT: ESA/ATG MEDIALAB. JUPITER: NASA/ESA/J. NICHOLS (UNIVERSITY OF LEICESTER). GANYMEDE: NASA/JPL. IO: NASA/JPL/UNIVERSITY OF ARIZONA. CALLISTO AND EUROPA: NASA/JPL/DLR

NS

Europa, Ganymede, and Callisto harbor potential subsurface oceans. Soon, JUICE will show them as never before.

BY BEN EVANS

DOMINATING THE PLANETS with its bulk, mighty Jupiter offers key insights into the formation of our solar system. And its three large icy moons have long sparked curiosity, not necessarily for their frozen surfaces, but for what potentially lies beneath: liquid water oceans that may even be capable of hosting life.

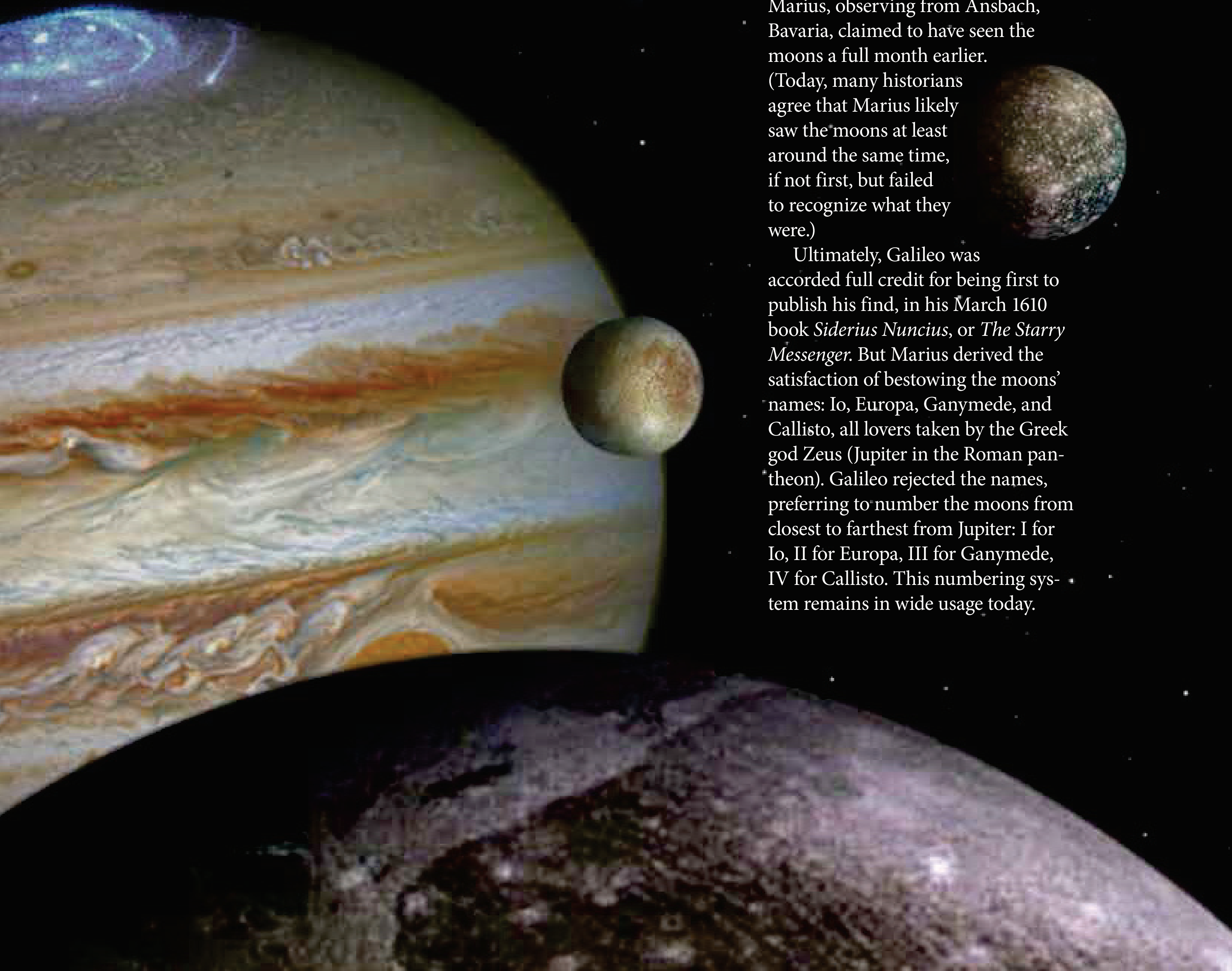
This April, the European Space Agency's JUpiter ICy moons Explorer (JUICE) will embark on a voyage to the gas giant. Once there, it will spend several years studying deep-frozen Europa, primordial Callisto, and giant Ganymede, determining how they formed and how they fit within the wider jovian system.

The Galilean moons

In the winter of 1609–1610, Galileo Galilei turned his handcrafted spyglass to the cloudy heavens above Padua, west of Venice, and spotted four moons circling Jupiter. They were the first natural satellites ever discovered around another planet.

German astronomer Simon Marius, observing from Ansbach, Bavaria, claimed to have seen the moons a full month earlier. (Today, many historians agree that Marius likely saw the moons at least around the same time, if not first, but failed to recognize what they were.)

Ultimately, Galileo was accorded full credit for being first to publish his find, in his March 1610 book *Siderius Nuncius*, or *The Starry Messenger*. But Marius derived the satisfaction of bestowing the moons' names: Io, Europa, Ganymede, and Callisto, all lovers taken by the Greek god Zeus (Jupiter in the Roman pantheon). Galileo rejected the names, preferring to number the moons from closest to farthest from Jupiter: I for Io, II for Europa, III for Ganymede, IV for Callisto. This numbering system remains in wide usage today.



JUICE will lift off atop an Ariane 5 rocket similar to the one shown here. The mission will also mark the 117th and last time this launch vehicle will ever be used. ESA/CNES/ARIANESPACE-SERVICE OPTIQUE CSG

All circled the planet synchronously, with one hemisphere perpetually directed toward their colossal host and the other facing the frigid cold of deep space. But before the Space Age, little else could be learned, as even the best telescopes could not resolve the moons, instead rendering them as meager points of light.

Our earliest robotic visitors, Pioneer 10 and 11, which reached Jupiter in December 1973 and December 1974, respectively, furnished little additional detail. It wasn't until March and July 1979, when Voyager 1 and 2 visited Jupiter, that we got an up-close view. Later, the Galileo probe flew past each moon several times between 1996 and 2002.

Nearest to Jupiter, Io is the odd moon out — not icy but incredibly volcanic, more so than any other solar system world. Regularly squeezed and stretched between Jupiter and its fellow large moons, Io hosts hundreds of volcanoes and an ever-changing surface with lakes not of water, but of molten lava.

Beyond Io are icy Europa, Ganymede, and Callisto. Decades of research have shown they have remarkably diverse histories — but all share the same secret: a potential saltwater ocean hidden beneath a frozen exterior.

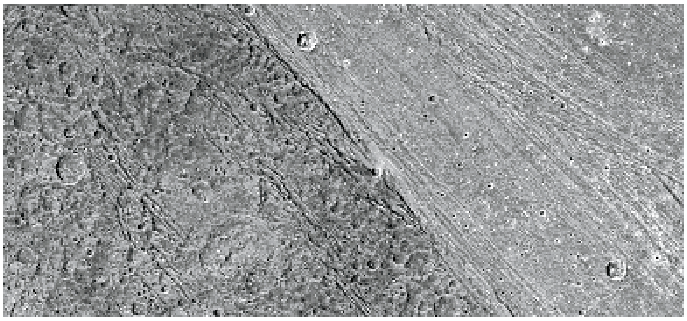
Beneath the surface

Galileo's discovery of glacier-like features and traces of cryovolcanism on Europa in early 1997 prompted notions that deep beneath its granite-hard crust might reside a layer of liquid water or warm, slushy ice up to 100 miles (150 kilometers) deep. Its presence has been further evidenced by Hubble Space Telescope (HST) observations indicating the consistent presence of water vapor in the moon's atmosphere, in one case reaching 125 miles (200 km) above the surface before falling back to the ground. And several studies have suggested that dark streaks on Europa could be salt deposits left behind by seawater melting its way through the crust and evaporating, bolstering arguments for a warm europan ocean — though some scientists doubt the two layers have ever interacted.

Researchers hypothesize that heat from tidal flexing could keep Europa's ocean liquid. Additionally, the moon's interior may be hot enough to melt its rocky mantle, fueling underwater volcanoes and vents. On Earth, such features can provide rich resources for life. (See "Searching for life on watery worlds" on page 36 to learn more.)

Nonetheless, the nature of the moon's hypothetical ocean remains open to conjecture. Indeed, differing models of the europan interior have argued for a crust as thin as 660 feet (200 meters) in places or as thick as 20 miles (30 km).

Meanwhile, Galileo measurements of Ganymede's magnetic field are highly suggestive of the presence of electrically conducting fluid, such as an ocean with salinity



The huge moon Ganymede is marked by two distinct types of terrain: old, dark, and cratered (left); and young, bright, and smooth (right). Galileo imaged this unique location where the two meet. NASA/JPL/DLR

Juno snapped this stunning image of Ganymede in June 2021, showing off the moon's cratered surface and patchwork of light and dark features. NASA/JPL-CALTECH/SWRI/MSSS/KALLEHEIKKI KANNISTO © CC BY

▲ Galileo showed off Europa's complex icy surface, crisscrossed by long cracks and ridges in the frozen crust. This view shows Europa in true color, as the human eye would perceive it. NASA/JPL-CALTECH/SETI INSTITUTE

◀ Planetary scientists believe that portions of Europa's disrupted terrain could indicate the influence of an underground ocean on the surface above. Reddish features are associated with hydrated salts, such as magnesium sulfate and sulfuric acid. Bluer and whiter areas are purer water ice. NASA/JPL-CALTECH/SETI INSTITUTE

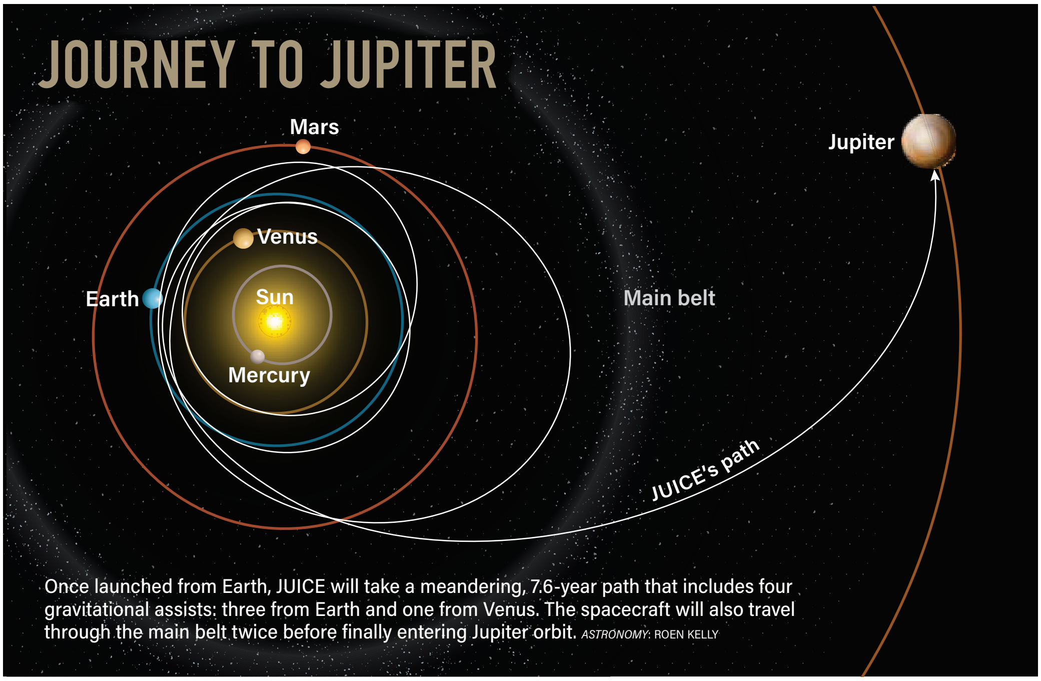
on par with earthly seawater. Galileo also indicated that, like Europa, Ganymede's surface exhibits salt minerals that could have been left by exposure to saltwater. A 2015 analysis of the moon's magnetic field based on observations of its aurorae by HST suggests that Ganymede might harbor the largest ocean in the solar system, some 10 times deeper than Earth's own oceans, less than 200 miles (330 km) below the surface. Hubble data even indicate Ganymede may possess a "stack" of multiple ocean layers separated by different phases of ice and extending right down to its icy mantle.

Galileo observations of Callisto's magnetic field also hinted at a saltwater ocean, possibly deep below the cratered surface — 155 miles (250 km) or more. Though the world is geologically quiescent, its ocean could be kept liquid through insulation from the crust above and heating from below by radioactivity in the core.

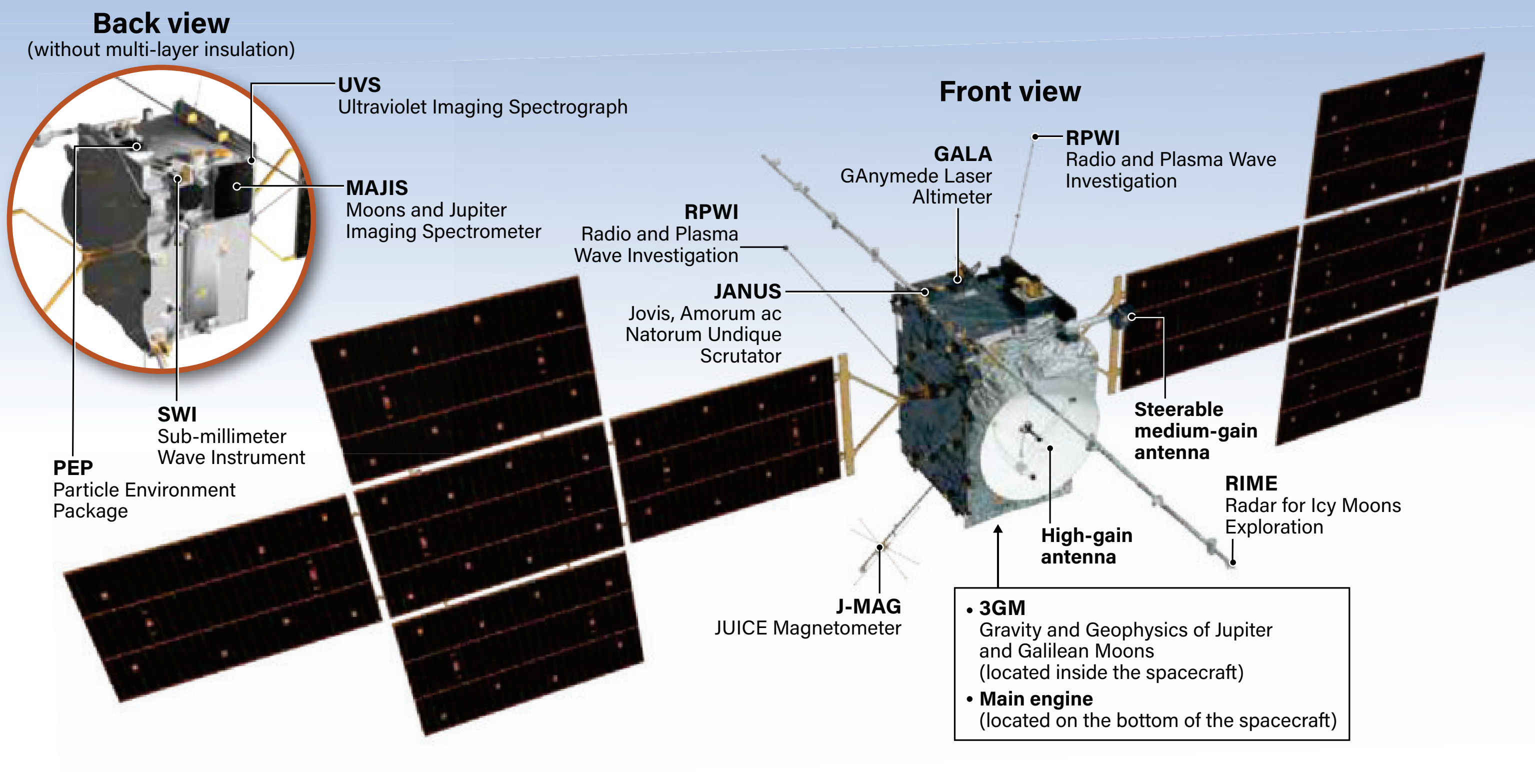
With its warmer interior and geologic activity, many researchers see Europa as the most likely breeding ground for potential life in the jovian system. But scientists aren't yet sure whether the thickness of its crust prevents sunlight and oxygen from reaching the subsurface ocean. Ganymede resides farther from Jupiter's radiation belts, which perhaps bumps up its habitability somewhat. And while it's possible that reactions between its water and rock mean Callisto's ocean could potentially support halophiles — salt-loving organisms found in some environments on Earth — the moon's insufficient internal energy reserves and geological "deadness" renders this prospect somewhat less likely.

Planning a visit

The tantalizing possibility of salty subsurface oceans — and perhaps even life — on these icy moons has put them high on the wish list of mission planners for decades. In October 2007, ESA short-listed a proposal for a mission called Laplace that would send a trio of spacecraft to Jupiter — including one dedicated to orbiting Europa and another that would make flybys of Ganymede and Callisto.



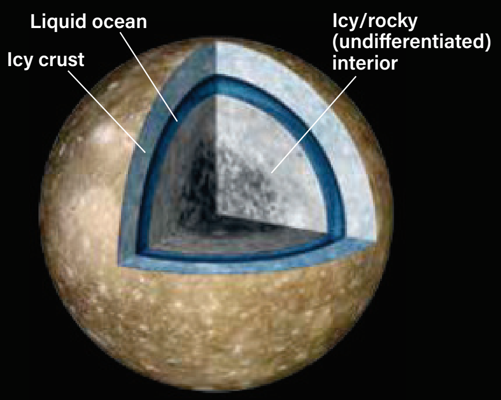
Once launched from Earth, JUICE will take a meandering, 7.6-year path that includes four gravitational assists: three from Earth and one from Venus. The spacecraft will also travel through the main belt twice before finally entering Jupiter orbit. *ASTRONOMY*: ROEN KELLY


Back view
(without multi-layer insulation)
UVS
Ultraviolet Imaging Spectrograph
MAJIS
Moons and Jupiter Imaging Spectrometer
SWI
Sub-millimeter Wave Instrument
PEP
Particle Environment Package
Front view
GALA
GAnymede Laser Altimeter
RPWI
Radio and Plasma Wave Investigation
RPWI
Radio and Plasma Wave Investigation
JANUS
Jovis, Amorum ac Natorum Undique Scrutator
Steerable medium-gain antenna
RIME
Radar for Icy Moons Exploration
High-gain antenna
J-MAG
JUICE Magnetometer
• 3GM
Gravity and Geophysics of Jupiter and Galilean Moons
(located inside the spacecraft)
• Main engine
(located on the bottom of the spacecraft)

THE GALILEAN MOONS

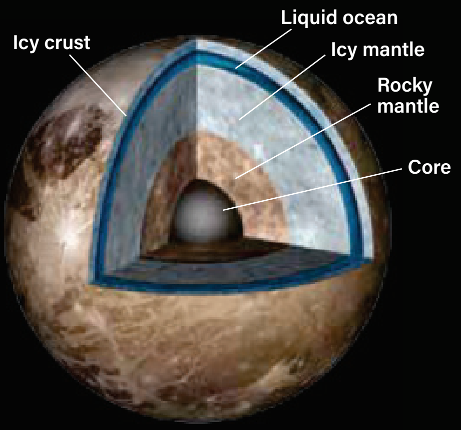
CALLISTO lies farthest from the worst of its giant host's lethal magnetospheric radiation. Additionally, it never fell victim to the savage gravitational tugging, squeezing, and mauling that Ganymede, Europa, and Io have, leading to an interior that never fully melted and is only partially differentiated. The least geologically active of the three icy worlds, battered Callisto evolved more benignly. The low levels of radiation coupled with the moon's geological stability have seen it considered prime real estate for a future human base. Callisto may have a liquid ocean, though it's likely buried deep below its surface.

Diameter: 3,000 miles (4,800 km)
1.17 million miles (1.88 million km) from Jupiter



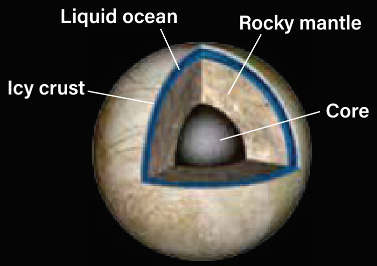
GANYMEDE is the largest moon in the solar system; it is wider (but less massive) than Mercury. The moon's two-toned surface reflects distinct terrain types: one dark and heavily cratered, the other brighter and overlaid by ridges and furrows. Both are ancient, at least 4 billion years old, and researchers divide the moon's geologic history into three phases: first characterized by impacts; then tectonic upheaval; and finally the current, mostly quiescent phase. The moon's magnetic field offers persuasive evidence for a liquid nickel-iron core several hundred miles thick and the Galileo mission discovered tantalizing hints of a salty subsurface ocean.

Diameter: 3,270 miles (5,260 km)
665,000 miles (1.1 million km) from Jupiter



EUROPA sits close enough to Jupiter that it is subjected to stronger tidal forces than Ganymede, which have kept it more geologically alive. Europa hosts a mixture of bright plains and mottled terrain, with ridgelike cracks and veinous linear scratches. A relative paucity of craters implies a surface some 20 million to 40 million years old in places, perhaps still in the throes of tectonic activity. Europa also has one of the solar system's brightest surfaces — it reflects 62 percent of the light that falls on it, akin to glacial ice — and likely possesses beneath its crust a warm, slushy ocean.

Diameter: 1,940 miles (3,100 km)
417,000 miles (671,000 km) from Jupiter



JUICE'S SCIENTIFIC PAYLOAD

JUICE carries a complement of 10 instruments to study aspects of Jupiter and its moons, including imagers, radar, and a magnetometer. An 11th experiment, called PRIDE, will use the craft's existing communications equipment. The delicate electronics are housed in lead to protect them from the harsh radiation environment around Jupiter, while the optical bench is made from carbon-fiber reinforced plastic, which is more stable during temperature changes than metals such as aluminum. J-MAG sits at the end of a 35-foot-long (10.6 m) boom to reduce interference from the spacecraft itself, while the huge, 915-square-foot (85 square meters) solar arrays will soak up the sunlight necessary for power. *ASTRONOMY*: ROEN KELLY

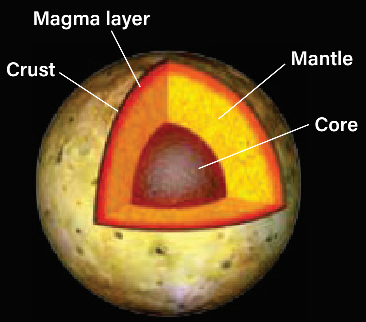
That same year, NASA began investigating its own mission to the Jupiter system. In early 2009, the two agencies agreed to a joint mission. NASA would build the $3.8-billion Europa orbiter, while ESA would construct a $1-billion craft to perform repeated flybys of Callisto before settling into orbit around Ganymede. Planners envisaged two separate launches around 2020, reaching Jupiter in late 2025 and early 2026 for three years of exploring not just the moons, but the entire jovian system.

But in March 2011, the U.S. National Academies' influential decadal survey of the planetary science community found that the massive budget for NASA's Europa orbiter would threaten too many other important missions. Facing budget cuts, NASA elected to pull out of the effort.

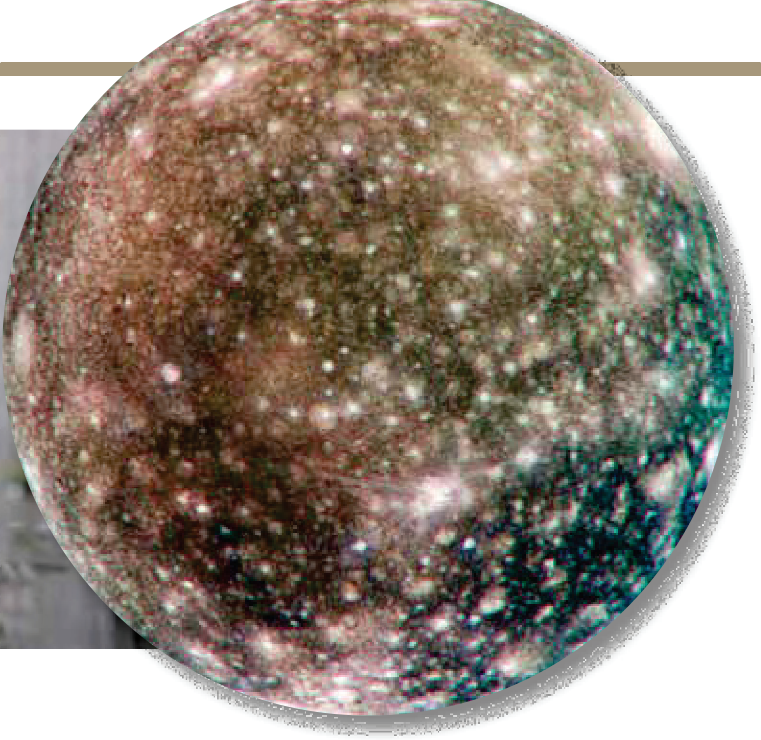
ESA continued to pursue its plans, revamping them yet again to encompass all three major icy moons: Europa, Ganymede, and Callisto. However, adding Europa posed a unique set of challenges. Europa's proximity to Jupiter means it lies deeper within the radiation belts that surround the planet, requiring heavy and expensive radiation-resistant electronics. Mission designers ultimately reached a compromise, whereby the probe would execute just two Europa flybys. These few, brief flybys would only minimally expose the craft to the intense radiation nearer the planet, meaning simpler, cheaper radiation shielding would suffice to protect its precious cargo of instruments. Planners also tweaked the probe's orbit around Jupiter, using multiple Callisto flybys to bump its inclination up to around

IO is the innermost Galilean moon. It is a violently volcanic world stretched by tides generated through interactions with Jupiter and its fellow moons. Its surface is pocked with volcanoes and lakes of molten lava, while its tenuous atmosphere is largely sulfur dioxide. Io has no water; thus, unlike its icy compatriots, it is likely too inhospitable for any type of life as we know it. Io and its passage through Jupiter's magnetic field have a profound effect on the gas giant, playing a role in generating the lightning and aurorae that light up the planet's atmosphere.

Diameter: 2,260 miles (3,640 km)
262,000 miles (422,000 km) from Jupiter



MOONS (SIZES TO SCALE): *ASTRONOMY*: ROEN KELLY. JUPITER (NOT TO SCALE): ALEXANDR YURTCHENKO/DREAMSTIME



▲ An engineer carefully checks one of JUICE's solar panels before integration with the spacecraft. The 10 panels will deploy in a cross-shaped pattern with five on either side of the craft. Each panel measures 8 feet by 11 feet (2.5 m x 3.5 m) and can withstand not only large temperature swings, but intense radiation as well. AIRBUS

▶ Galileo showed quiescent Callisto as a relatively dark world of old terrain marked by brighter, younger craters. The color variations seen here are real, and likely indicate differences in composition — brighter regions are icier than the darker, eroded areas. NASA/JPL/DLR

30°, depending on the final mission profile, ideally allowing it to study Jupiter's poles.

The mission, renamed JUICE, was estimated to cost roughly 1.1 billion euros ($1.2 billion USD). It received ESA approval in May 2012, with a launch in May or June 2022 and backup opportunities the following year. JUICE was projected to reach Jupiter in 7.6 years, after traversing 373 million miles (600 million km).

In early 2013, 10 scientific instruments and one experiment were selected. They fell into three groups: four remote-sensing instruments, three geophysics instruments, and three in-situ payloads.

The remote-sensing suite includes the JANUS camera. (JANUS stands for *Jovis, Amorum ac Natorum Undique Scrutator*, a Latin phrase that translates to "comprehensive observation of Jupiter, his love affairs, and descendants.") It will image most targets at resolutions better than 1,300 feet (400 m) per pixel, though some may be resolved as fine as 8 feet (2.4 m). JANUS will examine the moons at a global, regional, and local level, as well as map Jupiter's roiling clouds.

The visible and near-infrared Moons and Jupiter Imaging Spectrometer (MAJIS) will observe tropospheric clouds, gas composition, and aurorae in the jovian atmosphere, plus surface ices and minerals on Ganymede, Europa, and Callisto.

The Ultraviolet Imaging Spectrograph (UVS) will examine the moons' outermost atmospheres and Jupiter's aurorae and upper atmosphere. The Sub-millimeter Wave Instrument (SWI) will alternate its focus between Jupiter's rings and atmosphere and the three moons.

Leading JUICE's geophysics payload is the GAnymede Laser Altimeter (GALA), which will perform topographical measurements with a vertical resolution as fine as 3.9 inches (10 centimeters) at low altitudes. The Radar for Icy Moons Exploration (RIME) will probe the moons' subsurface structures as deep as 12 miles (20 km). RIME can also achieve a vertical resolution as fine as 100 feet (30 m) to a depth of 5.6 miles (9 km) in ice. The Gravity and Geophysics of Jupiter and Galilean Moons (3GM) will use radio waves to trace the strength of Ganymede's

JUICE UP YOUR ROCKET!

WHEN THE 17-STORY-HIGH ARIANE 5 carrying JUICE ascends from its launchpad, on the rocket's fairing will stand a 10-by-13-foot (3 by 4 meters) image. It depicts a blue-green Earth tenderly handing Europe's intrepid robotic visitor over to multihued Jupiter. Surrounding their parent planet are three icy moons: one cautious, another excited, the third fast asleep.

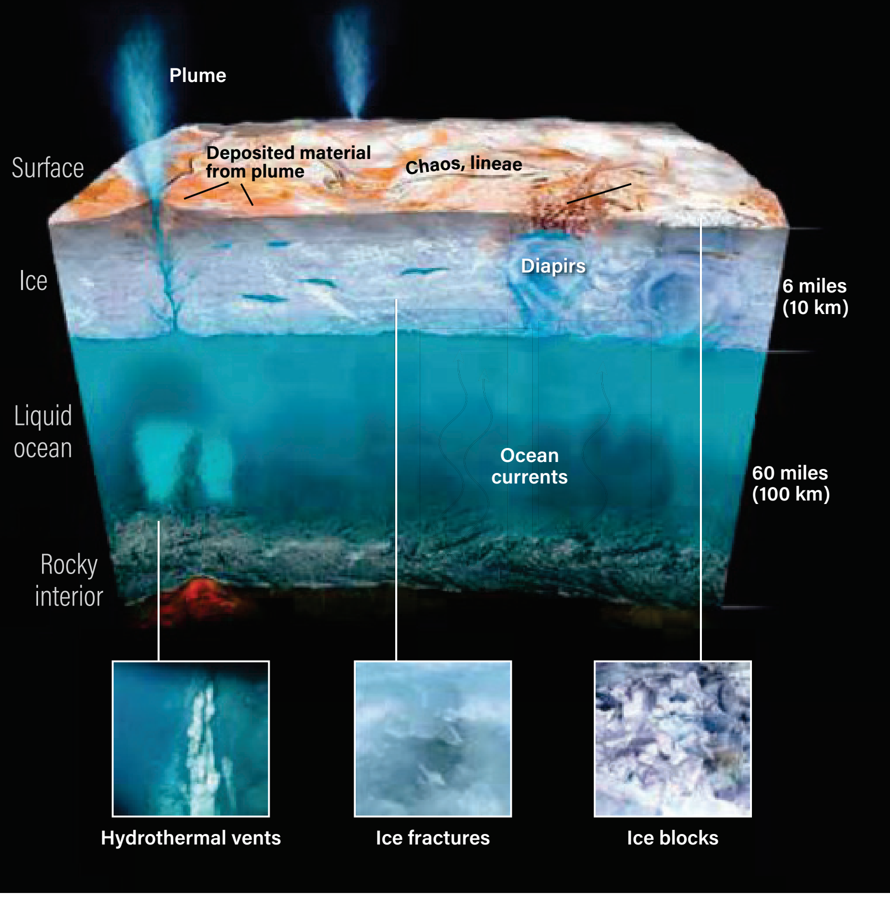
ESA

The scene arose from the mind of an 8-year-old girl named Yaryna from Ukraine. She was among more than 2,600 children from 63 nations who submitted their artwork to ESA in early 2021 for the "JUICE Up Your Rocket!" contest. In addition to ferrying planetary scientists' dearest hopes for learning more about how the Jupiter system — and our larger solar system — formed, Yaryna's creation will accompany JUICE on the first steps of its journey, carrying the hopes of a new generation. —*B.E.*

gravitational field and further measure the extent of any subsurface ocean in the three icy moons.

The Particle Environment Package (PEP), Radio and Plasma Wave Investigation (RPWI), and JUICE Magnetometer (J-MAG) will study the magnetic and plasma environment in the jovian system, plus investigate how the magnetic fields of Jupiter and Ganymede interact. And the Planetary Radio Interferometer and Doppler Experiment (PRIDE) will communicate with Earth-based radio telescopes to precisely map the spacecraft's location in space, yielding detailed information about the planet and moons' gravitational fields.

INSIDE EUROPA



Europa's warm interior could generate hydrothermal vents on the moon's ocean floors that release heat and material into the subsurface ocean. Warm water rising toward the bottom of the icy shell could cause cracks and other features, while large chunks of the surface — called ice rafts — may detach and float to new locations. Plumes could spout the ocean's contents high above the moon. *ASTRONOMY*: ROEN KELLY

Path to exploration

Scheduled to launch between April 5 and 25, JUICE will spend three months completing a near-Earth commissioning phase. Next, the spacecraft will enter a lengthy cruise phase that ends in January 2031, when it will begin gearing up to enter Jupiter orbit. During the cruise, there will be little input from Earth, with one check-in each week. JUICE's instruments will also be checked twice yearly during the long, dark trek to Jupiter.

To get to the gas giant, the spacecraft requires a series of gravitational boosts from four planetary encounters. These kick off with a first-of-its-kind dual flyby of the Earth-Moon system, known as a lunar-Earth gravity assist, in August 2024. JUICE will first get an assist from our Moon, then 36 hours later receive another from our home planet.

A year later, in August 2025, JUICE will pass Venus before its lazy, looping solar orbit provides two final Earth flybys in September 2026 and January 2029. JUICE will then hurtle through the main belt twice, possibly passing at close range to asteroid 223 Rosa in October 2029.

Traveling so close to and so far from the Sun imposes critical demands on the spacecraft and its twin solar arrays. Each array comprises five panels of gallium arsenide cells, totaling 915 square feet (85 square meters) and furnishing 820 watts of electricity. During its Venus flyby, the arrays must be tilted to prevent damage from excessive temperatures, while at jovian distances, incident sunlight will be 25 times weaker than near Earth. High-efficiency, multi-layered insulation will help to moderate external temperatures when JUICE is nearest the Sun, and also limit heat leakage at distant Jupiter.

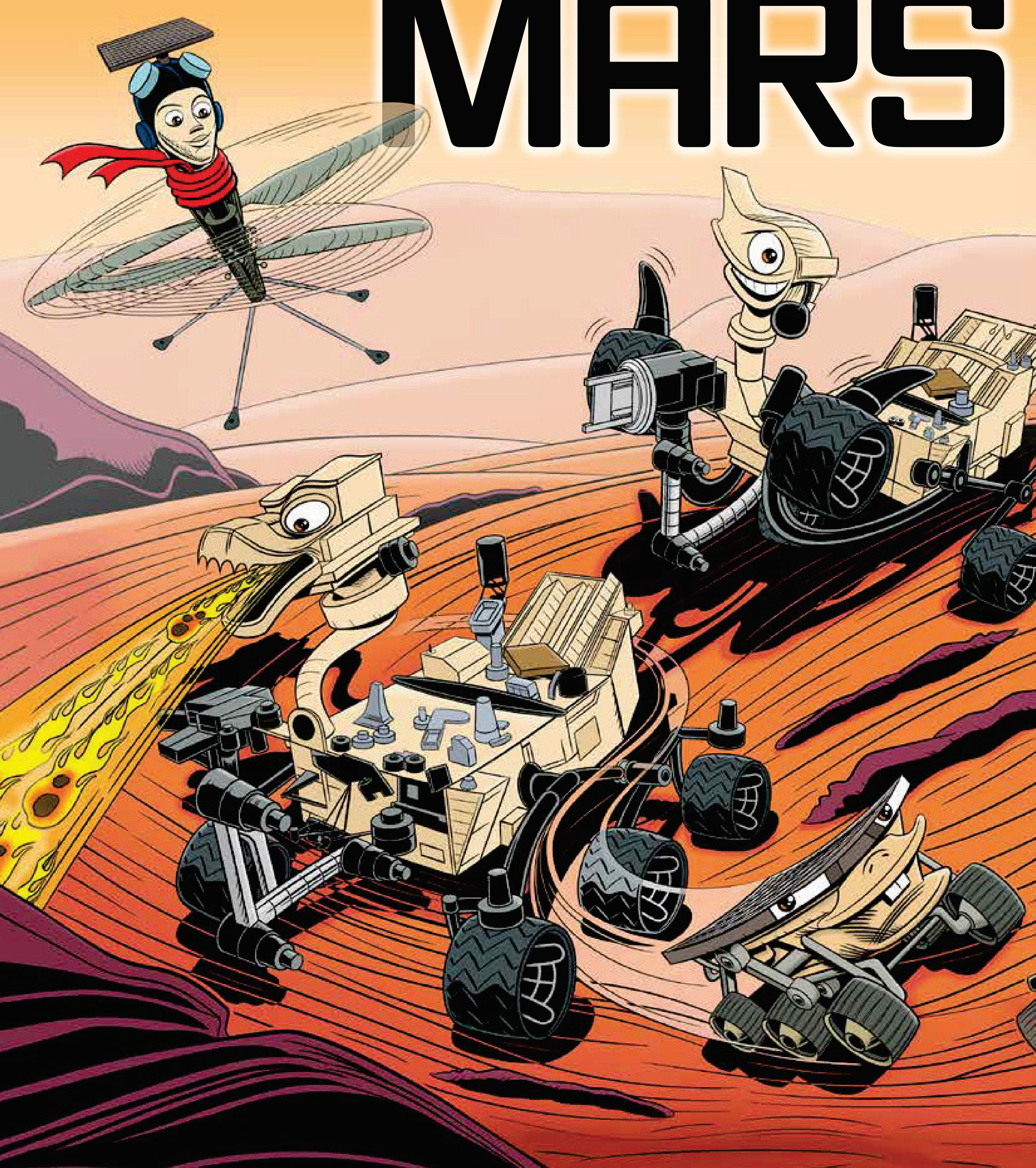
Arriving in the jovian realm in July 2031, JUICE will execute its first flyby of Ganymede before entering an elongated orbit around Jupiter. Over time, this orbit will be lowered and circularized. Two encounters with Europa are targeted for July 2032, after which the spacecraft will gradually boost its inclination through successive Callisto flybys between August 2032 and August 2033. This will set up its transfer to Ganymede. JUICE will enter orbit around the giant moon in December 2034 for almost a year of close-range observations, becoming the first spacecraft in history to orbit a natural satellite other than our Moon.

Its initial orbit around Ganymede will be highly elliptical, as JUICE undertakes a global geological mapping campaign. The altitude will be gradually adjusted to 310 miles (500 km), allowing JUICE to investigate Ganymede's subsurface ocean and deeper interior, as well as its icy shell, atmosphere, and plasma environment. After its propellant finally runs out, JUICE will naturally impact Ganymede's surface sometime late in 2035.

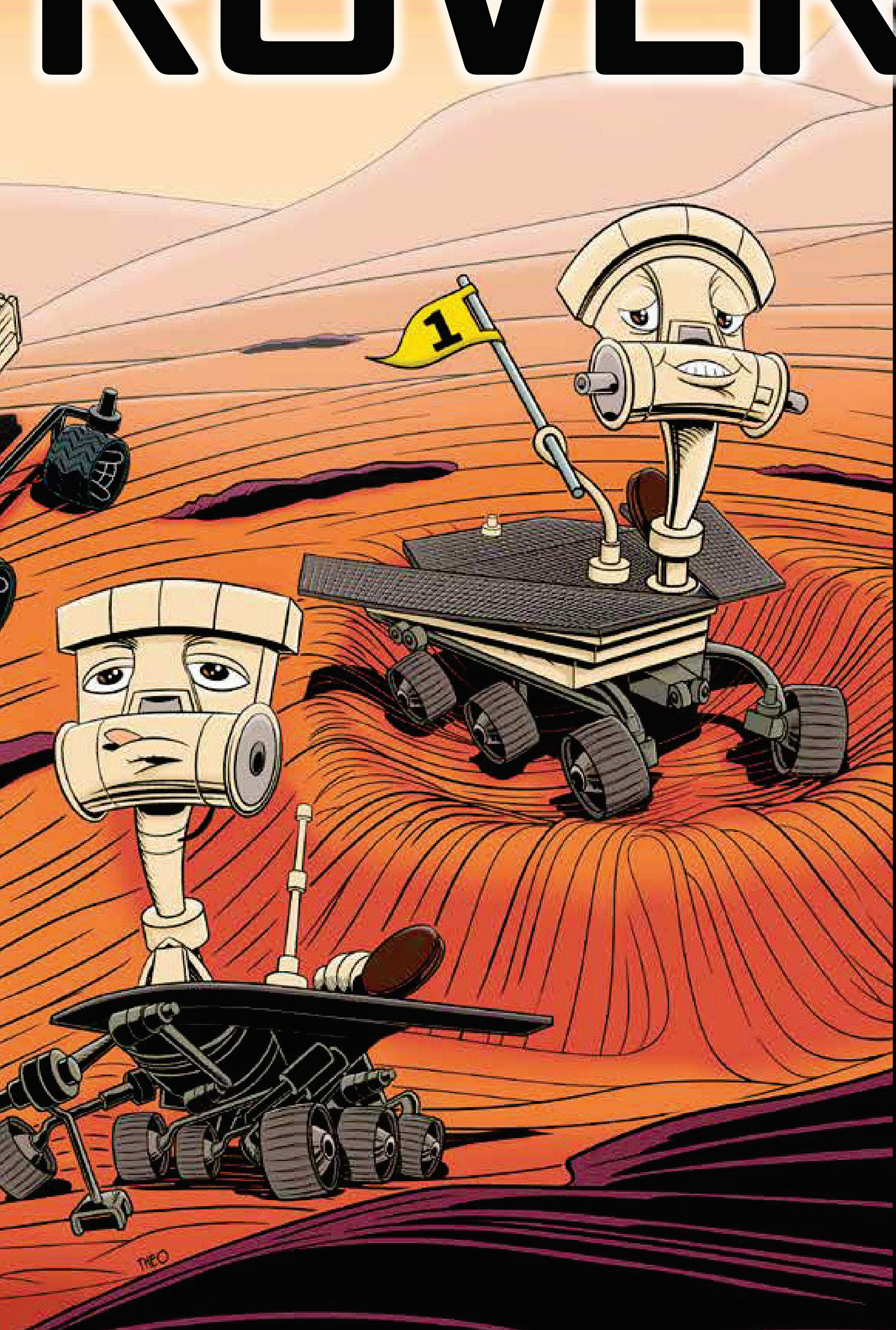
As Europe's first independent foray beyond the asteroid belt, JUICE is breathtaking in its scope and spellbinding in its daring. The 10th spacecraft to visit the jovian system, it follows in the footsteps of those that came before but will carve out its own important niche in the history books as the best chance of finding water oceans — and life — beyond our own small patch of the solar system.

Ben Evans *has written extensively on the history of human spaceflight and robotic exploration of the solar system.*

The many personalities
MARS



# of NASA's
ROVERS



The first explorers of Mars include the rich and entitled, the bratty kids, the barnstorming aviators, and the selfie-obsessed social media sensations. (Did you think we meant humans?)

STORY BY MELISSA RICE AND ILLUSTRATIONS BY THEO COBB

Rovers may be lifeless robotic hunks of metal, but to the scientists and engineers who work on them, each mission has its own personality. Clockwise from upper left: Ingenuity, Perseverance, Opportunity, Spirit, Sojourner, and Curiosity.

In January 2004, two rovers opened their eyes for the first time on Mars. They were identical twin robots with the same goal: to search for signs of past water in the rocks and minerals. But like any set of twins, they developed distinct personalities, shaped by their different environments and circumstances.

Opportunity — or Oppy, as it was affectionately called by the mission team — immediately found evidence for ancient water while Spirit searched for years to discover the same. Oppy covered a marathon's distance with relative ease; Spirit busted a wheel and limped backward. Near the equator, Oppy was exploring year round; farther south, Spirit had to hunker down for each cold, dark martian winter. When Oppy got stuck in the sand, it struggled but got free. When Spirit got stuck in the sand, it struggled and struggled … and then winter came, and it died.

As a graduate student, I was part of the mission science team for both rovers, helping with their day-to-day operations. We talked about them as if they were different people: Oppy was the golden child, and Spirit had to fight for everything. I loved them both, but I *liked* Spirit better — the kid had moxie.

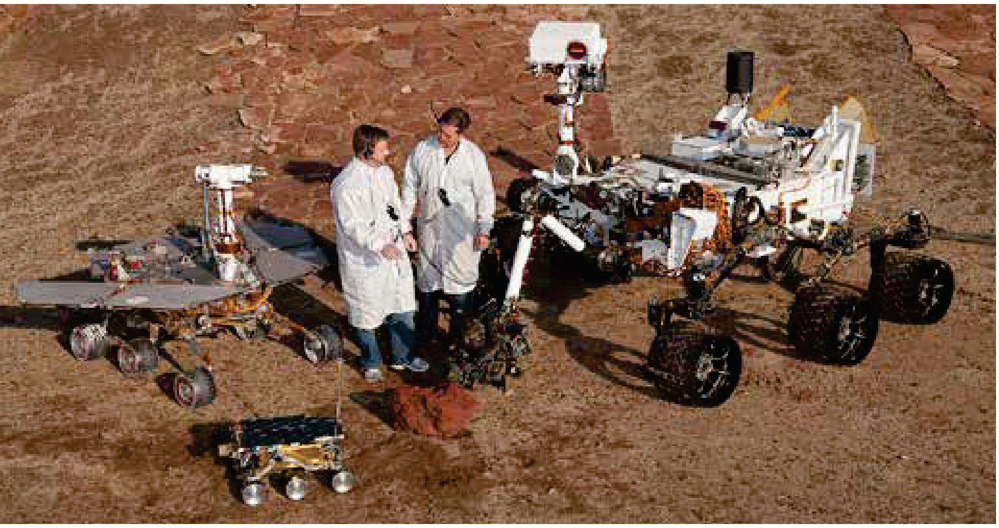
Personifying Spirit and Oppy was easy to do because they were designed to be like us in some ways. Their science cameras had a resolution equivalent to 20/20 human vision and were placed at the average height of a person's eyes. Their robotic arms were the length of a long human arm, with shoulder, elbow, and wrist joints. And they were so darn cute, with those big, round doe eyes.

Let's be clear: Spirit and Oppy did not have personalities. They were hunks of metal. The rovers' *missions*, however, each had a unique personality shaped by engineering quirks, scientific fortunes (and misfortunes), and the people on their teams. If you were to teleport me blindfolded into one of the rover's operation rooms circa 2008, I could tell you whether it was Spirit's or Oppy's plan being discussed just from the vibe.

Since the Spirit and Opportunity missions ended, I've continued operating Mars rovers as part of the Curiosity and Perseverance (Percy) mission science teams. These newer-generation robots are less humanlike than their predecessors: They're bigger, beefier, less symmetrical, and, for all those reasons, decidedly less cute. But their missions still have distinct personalities. I can't help but project those onto the rovers themselves, and I enjoy speculating about the kinds of people these rovers would be. *Would Curiosity be into Steely Dan? Would Percy wear an ascot?*

I asked several of my scientific colleagues — fellow Mars rover veterans — what they think about the missions' different personalities. Even the most formidable, uncompromisingly logical minds in the business admit to personifying the different robotic explorers.

What follows is a character study of each NASA craft on Mars with wheels or rotors. While I draw upon the insights and stories from my colleagues, these depictions and taglines are highly subjective, often ridiculous, and ultimately my own.



Three generations of Mars rovers are represented in this portrait. In front on the left is Sojourner; behind it is a test rover that is a cousin of Spirit and Opportunity; at right is a test rover for Curiosity. NASA/JPL-CALTECH

SPIRIT • 2004-11

SPIRIT AND OPPORTUNITY WERE THE TWINS of NASA's Mars Exploration Rover mission, but Spirit always had a harder go of it. Spirit was, as several colleagues put it, a "blue-collar" kind of rover. "It went to work each day with lunch pail in hand, ready to work on rocky terrain," says Jeff.

Early in its mission — only its 17th martian day, or sol — a problem with the rover's flash memory made its computer reboot over and over all through the night, draining its battery. Many team members thought this would be the end of Spirit, but the engineers sent commands to reformat its entire flash memory system, saving the mission. Spirit was up and running again by Sol 32.

And that's how it went: The rover would have a major setback, and the science team would find a way to overcome it. Even Spirit's landing site reflected this pattern. NASA sent Spirit to Gusev Crater, expecting to find rocks that formed in an ancient lake. Instead, Spirit saw only basaltic rocks made in lava flows. Jim Bell, the principal investigator for the rovers' Panoramic Cameras, describes the Gusev plains as "a basaltic prison." But in typical Spirit style,

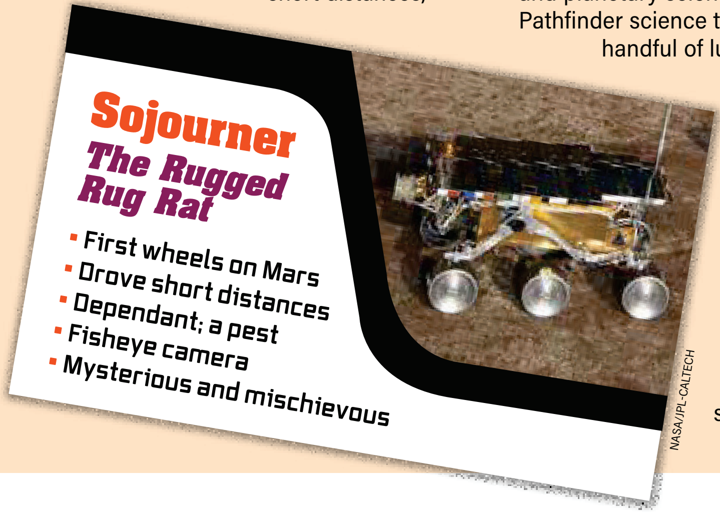
SOJOURNER • 1997

THE FIRST WHEELS ON MARS were those of the Sojourner rover, which was a technology demonstration and part of NASA's Mars Pathfinder mission. Roughly the size of a microwave oven, Sojourner drove only short distances, always staying within view of the Pathfinder lander, like a bear cub that couldn't stray too far from its momma.

Sojourner had "the personality of a toddler," according to Jeff Johnson, a geologist and planetary scientist who was part of the Pathfinder science team. Jeff is one of a handful of lucky scientists who have been part of every NASA Mars rover mission to date.

"We hoped it went in the direction we said, but its final location wasn't always as intended," Jeff says. "We were not quite sure how it would respond to specific commands, so we learned its limitations and strengths by observing. Its fisheye camera made everything look big and fuzzy, but we marveled at the views anyway."

Sojourner could be a pest sometimes, getting in the way of the serious work Pathfinder was doing. A few times in its short mission, the robot toddler photobombed the panoramic images that the lander's cameras were taking. From these stories, I always pictured Sojourner as a mischievous rug rat with its hand in the cookie jar.



Sojourner

The Rugged Rug Rat

- First wheels on Mars
- Drove short distances
- Dependant; a pest
- Fisheye camera
- Mysterious and mischievous

NASA/JPL-CALTECH

the team made a jailbreak: They drove the rover east for two years toward a row of hills beckoning on the horizon.

Along the way, Spirit's solar panels got dusty, blocking their view of the Sun and limiting the rover's power. The team had seen dust devils swirling ominously nearby, and one scored a direct hit on Spirit. But it didn't topple the rover or cause any harm. Instead, it swept Spirit's solar panels clean, restoring the rover to full power. Several more times during its extended mission, Spirit would luck into these dust devil cleaning events, the closest thing on Mars to a car wash.

When Spirit arrived at the Columbia Hills, it summited the highest peak, but another major setback struck: Its right front wheel stopped turning. For the rest of its mission, Spirit had to drive backward, dragging its dead wheel behind it and digging a trench in the dirt the whole way. This slowed things down, but ultimately led to one of the most exciting discoveries of the mission.

"I've never seen anything like this on Mars," Jim told me when I met with him for the first time as a green graduate student. "What the heck is this stuff?" he asked, pointing to a bright yellow streak in Spirit's wheel trench.

I had no idea, but I would spend the next five years studying these bright soils that Spirit periodically churned up in its wake. They were sulfates and opaline silica, the kinds of minerals that form in hot spring environments — the ancient Mars equivalent of Yellowstone National Park. Just think, the minerals were buried only an inch below the surface, but had Spirit's wheel not been broken, we would never have seen them.

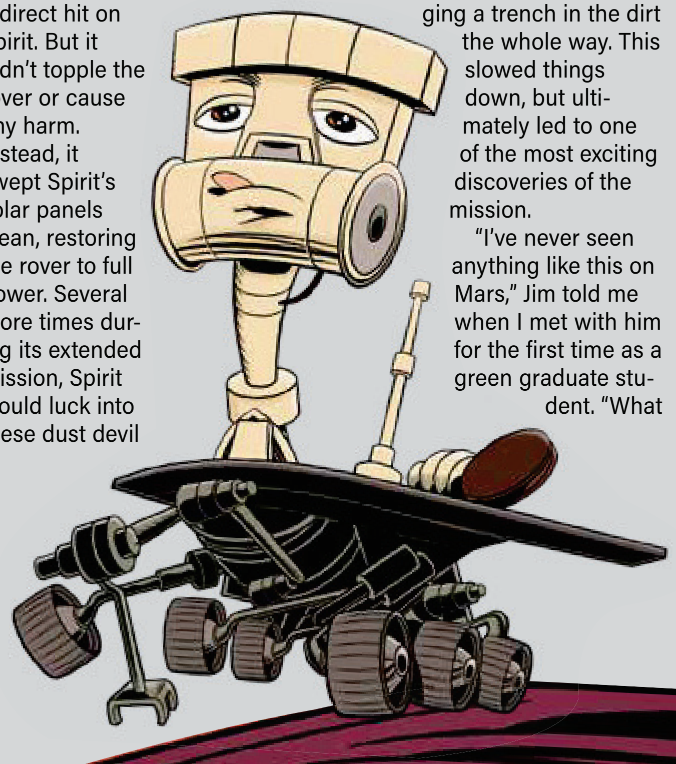
Those bright soils are exactly what Spirit got stuck in on May 1, 2009, spelling the end of the rover's mission. Team members wore shirts that said "Free Spirit" while they practiced maneuvers with a test-bed rover at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, trying anything and everything to excavate the rover from its sand trap. But Spirit's luck had finally run out.

Spirit

The Luckiest Unlucky Rover

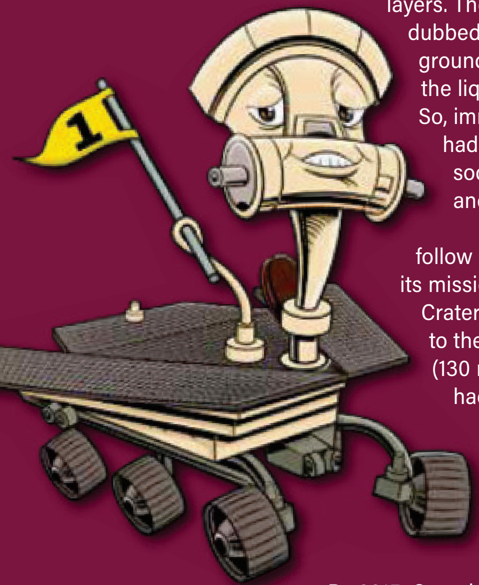
- Twin of Opportunity
- "Blue-collar" worker
- Weathered setbacks
- Broken right front wheel
- Dug out minerals

NASA/JPL/CORNELL UNIVERSITY



OPPORTUNITY • 2004-18

OPPORTUNITY'S LANDING IN MERIDIANI PLANUM was an interplanetary hole-in-one: The rover wound up in a small impact crater just 72 feet (22 meters) across, facing a wall of exposed, layered bedrock. Bedrock is greatly coveted by Mars explorers — it is the planet's exoskeleton. This was the very first sedimentary bedrock encountered on Mars, made of sandstones that formed in shallow water. And, to boot, small spheres of hematite were embedded in the sandstone layers. These "blueberries," as the team dubbed them, had formed from groundwater, precipitating out as the liquid trickled through the rocks. So, immediately after landing, Oppy had discovered two distinct episodes of water activity on ancient Mars.



That kind of success would follow Oppy throughout the rest of its mission. It climbed out of Eagle Crater and drove across the plains to the bigger, 430-foot-wide (130 m) Endurance Crater, which had even more sandstone layers exposed. Then it cruised over to Victoria Crater, half a mile (0.8 kilometer) wide, and finally, Endeavour, a behemoth of a crater 14 miles (22 km) across.

By 2015, Oppy had covered a marathon's distance. It was not a sprinter; Oppy's top speed was about 0.06 mph (0.1 km/h), which means it took close to an hour to drive the length of a football field. "Its traverses were characterized by lengthy periods of monotony, punctuated by astounding discoveries," Jeff says.

Sometimes, surprises would pop up during those long, boring stretches between craters. For example, Oppy drove right by its own heat shield. Next to it, the rover found a strangely pitted, metallic rock, unlike any seen on Mars before. The team measured its chemistry and concluded that it was not a Mars rock at all — it was an iron-nickel meteorite. Steve Squyres, the mission's principal investigator, quipped, "Quick, we've got to drive away from here! This is clearly the spot on Mars where big hunks of metal fall from the sky!"

Oppy's greatest luck was its longevity. "Oppy lasted like it was someone's grandmother," says Jeff, "continually sending good tidings in the form of data and images, fighting through another winter by adjusting its location for a warm orientation to the Sun, and benefiting from good wind and weather ... until it couldn't. It faced a quiet death with a fading memory, but it left a lasting legacy amid a bunch of tears."

Opportunity
The Martian Marathoner

- Twin of Spirit
- "Golden child"
- Drove long distances
- Found two episodes of water
- Lived a long life but arthritic in end

NASA/JPL-CALTECH

CURIOSITY • 2012-PRESENT

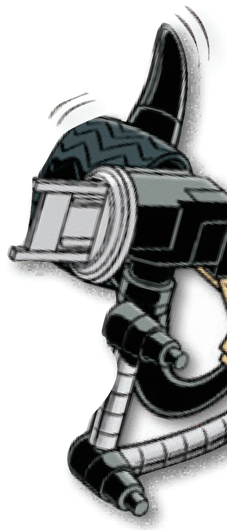
CURIOSITY IS A DIFFERENT KIND OF ROVER for a different era of Mars science. Whereas Spirit and Oppy were field geologists — scrappy, rugged explorers with a few tools on their belts — Curiosity is a meticulous lab scientist, hauling a truckload of sophisticated instruments. Weighing nearly 2,000 pounds (900 kilograms), it is more massive than all previous rovers combined. It needed a new landing system (the sky crane, as opposed to air bags) and a new power system (using the radioactive decay of plutonium rather than solar panels).

Its mast height is 7 feet tall (2.1 m), its arm 7 feet long (2.1 m), and the suite of instruments on its turret weighs close to 200 pounds (90 kg). That's so heavy that on Earth, Curiosity couldn't lift its outstretched arm under its own power. Curiosity is a true martian, built to survive and thrive in the Red Planet's low gravity.

It has a native diet, too: Curiosity eats Mars rocks for breakfast. It drills into them, crushes them, and ingests them. The Sample Analysis at Mars (SAM) instrument heats up the rock samples to hundreds of degrees and then analyzes the gases they emit. That can tell us what the rocks are made of and whether they contain organic molecules. Curiosity also blasts holes into rocks with a laser on its Chemistry Camera (ChemCam), which sits atop its mast like an off-center cyclops eye. I think of Curiosity as a beast, a dragon with a fire roaring in its belly.

On the one-year anniversary of its landing,

The rovers' missions each had a unique personality shaped by engineering quirks, scientific fortunes (and misfortunes), and the people on their teams.

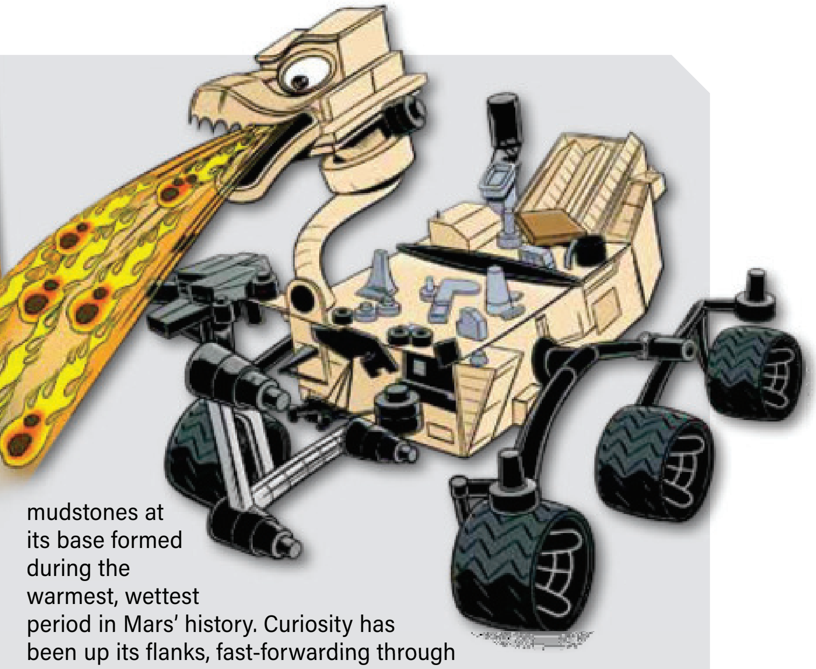


Curiosity

The Rock Eater

- Big and tall; self-reliant
- First without solar panels
- Eats and spits Mars rocks
- Rappelled out of a jetpack
- Sang "Happy Birthday" to itself

NASA/JPL-CALTECH/MSSS



Curiosity sang "Happy Birthday" to itself — the team commanded the SAM instrument to play the tones of the song. The collective response on the internet was pity: Poor, lonely Curiosity had to celebrate its birthday all by itself! But I thought it was badass: Curiosity makes its own party wherever it goes.

Curiosity "was at first like your uber-cool uncle who lived an adventurous lifestyle," says Jeff. "It felt like we really needed to consult the owner's manual a lot more to understand all the features this rover provided. As a result, we started slowly and worked up to its full capabilities." Curiosity was also "retrospective and vain enough to want to take selfies, perhaps more often than necessary," he says.

Curiosity's landing site in Gale Crater was next to Mount Sharp, a towering mountain of sedimentary rocks. The mudstones at its base formed during the warmest, wettest period in Mars' history. Curiosity has been up its flanks, fast-forwarding through martian time, studying the planet's changing climate as recorded in the bedrock.

All the driving over the past 10 years has wreaked havoc on Curiosity's wheels, which have been shredded by pointy rocks. But as of this writing, that's not slowing things down. "By now, it's a can-do machine with bad feet that probably won't stop until it's at the top of a mound with a spectacular view back toward its beginnings," Jeff says.

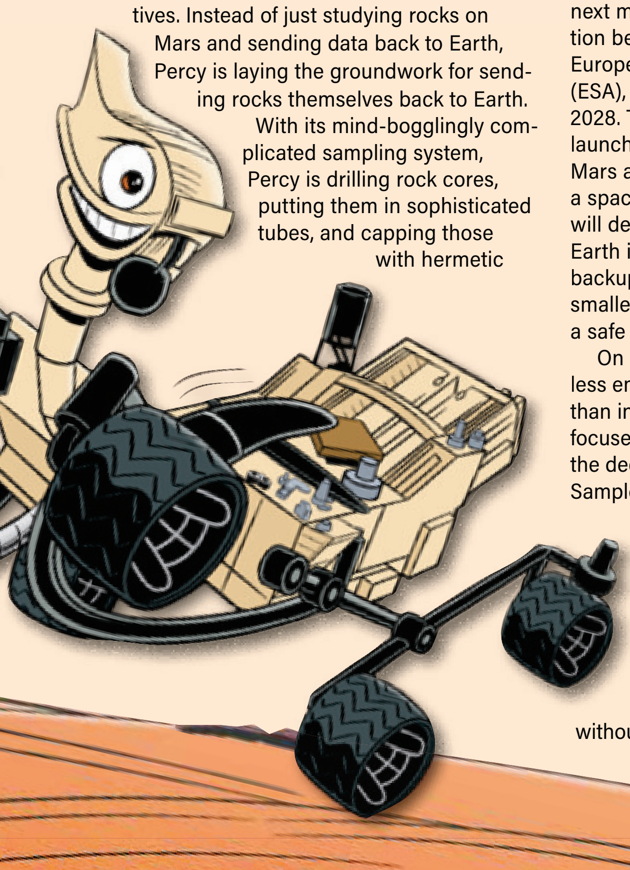
PERSEVERANCE • 2021-PRESENT

Perseverance

The Steely-Eyed Missile Rover

- Launched during COVID
- Smart, quick, and delivers
- Team player; can-do attitude
- Inherited Curiosity's appearance
- Collecting samples for return to Earth

NASA/JPL-CALTECH/MSSS



PERCY LOOKS LIKE A CLONE OF CURIOSITY, but it has very different objectives. Instead of just studying rocks on Mars and sending data back to Earth, Percy is laying the groundwork for sending rocks themselves back to Earth.

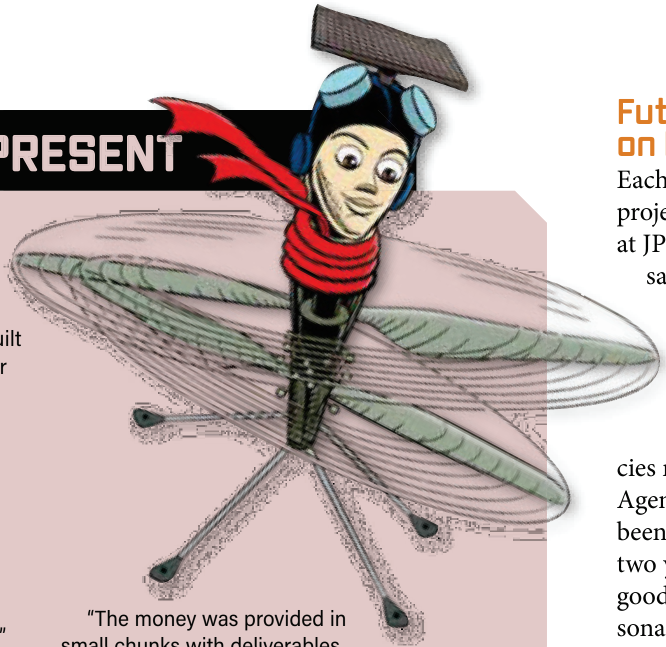
With its mind-bogglingly complicated sampling system, Percy is drilling rock cores, putting them in sophisticated tubes, and capping those with hermetic seals. The plan is for Percy to deliver its best samples to the next mission — a collaboration between NASA and the European Space Agency (ESA), scheduled to arrive in 2028. The samples will get launched into orbit around Mars and rendezvous with a spacecraft there, which will deliver the rocks to Earth in the 2030s. As a backup, Percy will drop a smaller cache of samples in a safe spot on the floor of Jezero Crater.

On Percy's operations team, there is much less emphasis on exploration and discovery than in previous missions; the team is laser-focused on the big-picture objectives. As part of the decadelong, international process of Mars Sample Return (MSR), the mission's character is necessarily bureaucratic. Jeff thinks of Percy "like a high-powered lawyer who works in high-rise offices with a lot riding on every decision. The rover is smart, quick, and delivers."

Percy is a go-getter with a haircut you can set your watch to. It finds ways to solve seemingly impossible problems without ever losing its cool. A global pandemic is raging during the launch window? No problem — Percy launched right on schedule. The pandemic means that scientists can't travel to JPL? No worries — we operated the rover via videoconference from our living rooms across the world. Percy accidentally pulverized its first rock sample while drilling it? Its next rock sample worked great.

During NASA's Apollo era, there was no greater praise for a flight controller than to be called a "steely-eyed missile man." According to astronaut Jim Lovell in his memoir *Lost Moon*, "There weren't many steely-eyed missile men in the NASA family. [Wernher] Von Braun was certainly one, [Chris] Kraft was certainly one, [Gene] Kranz was probably one too." In my mind, Percy is the first steely-eyed missile rover in the NASA family.

INGENUITY • 2021-PRESENT



THE INGENUITY HELICOPTER, which hitchhiked to Mars with Percy, was the first spacecraft to attempt powered flight in the atmosphere of another planet. Sojourner and Ingenuity have similarities: Both were built as tech demos by small teams working under incredible time pressure. But there are some differences, too.

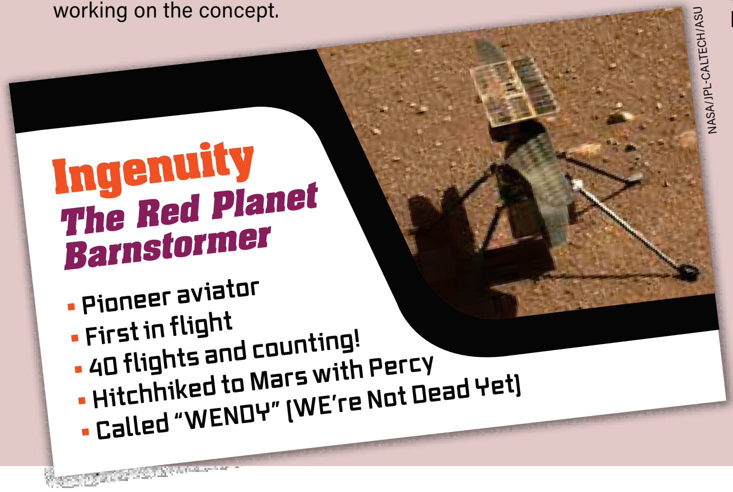
Sojourner's mission had a number of science objectives and a science team; Ingenuity's mission has neither. Flying five times was the extent of Ingenuity's goals. Ingenuity reminds me of Amelia Earhart, another no-nonsense aviation pioneer, who said, "I lay no claim to advancing scientific data other than advancing flying knowledge."

Ingenuity almost didn't happen. Matt Golombek, a Mars scientist who had worked on the Spirit and Oppy missions, originally submitted a proposal to NASA in 2014 for Percy to carry a "Mars Helicopter Scout" to help the rover plan its traverses, but it wasn't selected. However, NASA was intrigued by the idea and sent Matt's team some seed money to start working on the concept.

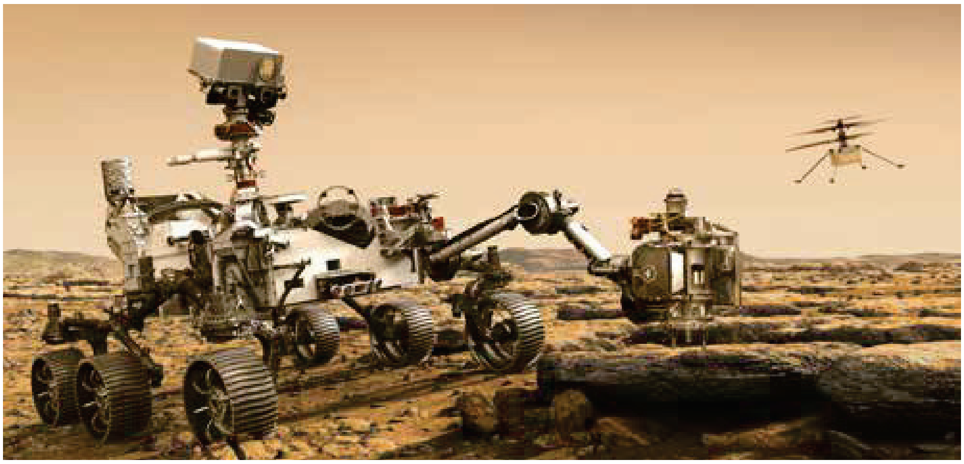
"The money was provided in small chunks with deliverables at the end of each," Matt says. "So during development, we never knew if we were really going to fly. We started using the phrase WENDY, for 'We're Not Dead Yet!'"

Ingenuity completed its first five flights with flying colors, so to speak, and it is still WENDY. It flies ahead of Percy, taking images that have helped the mission team plan the rover's traverse and identify outcrops to sample.

But it's the flying that's the point. Ingenuity is not a scientist's sidekick. It's more like a daredevil stunt pilot from the 1920s, showing off the capabilities of their sturdy aircraft and wowing crowds the world over.


Ingenuity
The Red Planet Barnstormer
▪ Pioneer aviator
▪ First in flight
▪ 40 flights and counting!
▪ Hitchhiked to Mars with Percy
▪ Called "WENDY" (WE're Not Dead Yet)

NASA/JPL-CALTECH/ASU



Ingenuity (right) has been serving as an aerial scout for Perseverance (left), but its primary purpose was to demonstrate that a helicopter drone could be built to fly on Mars. FUKUME/DREAMSTIME/NASA

Future personalities on Mars

Each of these missions are NASA projects operated by teams based at JPL; they all "grew up" in the same household. If these robot siblings turned out to have such distinct personalities, just imagine how different the missions from completely different space agencies must be! The Chinese Space Agency's first rover, Zhurong, has been exploring Mars for nearly two years. I do not yet have a good sense for Zhurong's personality, although I'm excited to learn more about its adventures as the mission continues.

Looking ahead, ESA will send its Rosalind Franklin rover to Mars in 2028 for the most ambitious life-seeking mission yet. The mission has suffered a decade of delays for various reasons, so already, its defining traits are patience, persistence, and grit. But what personality will it develop once the rover starts digging into Oxia Planum?

And then there's the big Mars Sample Return mission — a collaboration between NASA and ESA that will include a lander and two Ingenuity-like helicopters. The plan is for Percy to deliver its samples to the lander itself, but the helicopters can assist with grabbing samples if needed. What will the personality of a massive, multiagency mission like MSR look like? All I can predict is that just like every mission that has come before, it will be utterly unique.

Melissa Rice *is an associate professor of planetary science at Western Washington University and a science team member of NASA's ongoing Curiosity and Perseverance rover missions.*

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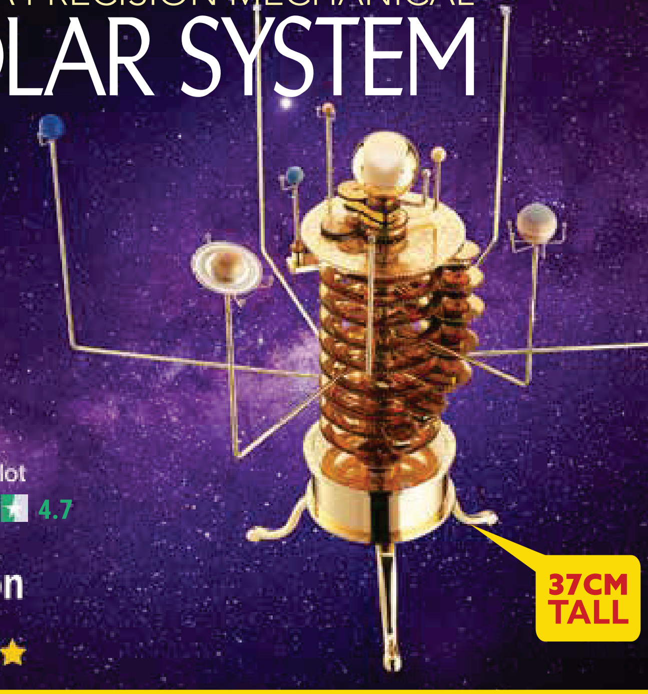

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SKY THIS MONTH

Visible to the naked eye
Visible with binoculars
Visible with a telescope

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.

BY MARTIN RATCLIFFE AND ALISTER LING

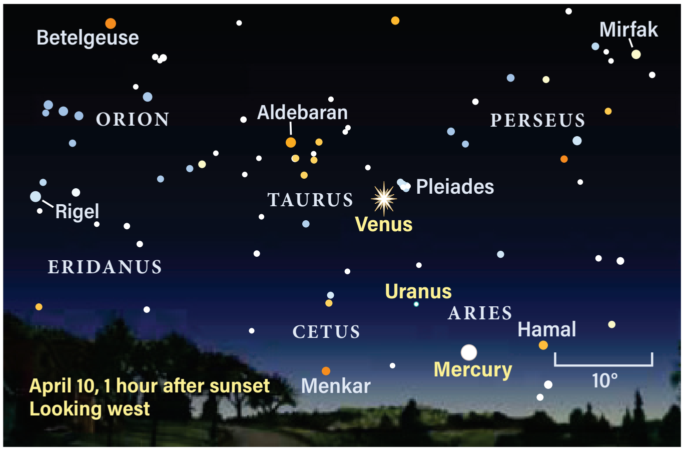
APRIL 2023

A rare hybrid eclipse

A diamond ring appears just before totality begins in 2009. This month, a hybrid eclipse that starts and ends as annular but is total for much of the track crosses from the Indian to Pacific oceans. ALAN DYER

Mercury and Venus put on their best display of the year this month. Watch them each evening, with Mercury at its best in the first two weeks of April. Mars continues to recede from Earth and is a nice 1st-magnitude object crossing Gemini. Saturn reappears in the morning sky, with better views late in the month — why not plan to view the April Lyrids and the ringed planet together? Jupiter is too close to the Sun for observation this month, while Uranus and Neptune are challenging.

Sunset scene



One day before Mercury reaches greatest elongation, Venus pairs nicely with the Pleiades. Uranus is visible with binoculars or a telescope. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

We begin our nightly tour of the planets with **Mercury**, which reaches its best evening appearance for the year during April and is visible almost all month. Look on April 1 for the innermost planet hanging 5° above the horizon 45 minutes after local sunset. Setting more than an hour after the Sun and shining at magnitude –1.1, it's an easy twilight target. One or two stars in Aries the Ram may pop into view nearby if your sky is clear enough. Venus hangs 21° higher than Mercury and is easy to spot west of Taurus.

Mercury passes some 8° due south of Hamal, the brightest star in Aries, on the 6th, then climbs to its greatest eastern elongation 19° from the Sun on April 11. The planet dims to magnitude –0.1 during this period as its phase declines from 76 percent to 39 percent lit.

On April 21, a crescent Moon joins Mercury low in the western sky. Look first for the Moon soon after sunset. However, Mercury has faded to magnitude 1.9 and will be difficult to spot as it stands nearly 9° due east of the Moon, at lower altitude. The Moon is 12° high and Mercury is just 5° above the horizon. Note that magnitude 5.9 **Uranus** lies within 4° of Mercury, but it will be most challenging to spot unless you're observing from high elevation with perfectly clear air. (Kitt Peak Observatory in Arizona is a good location.)

Venus dominates the evening sky, starting the month at magnitude –4. During April, it

OBSERVING HIGHLIGHT

MARS comes close to the star Mebsuta in Gemini, passing within ¼° on April 14.

takes a visually dynamic path between the stunning Pleiades (M45) and Hyades star clusters, which themselves just beckon for attention. Catch the scene soon after sunset and get ready for some great views as twilight falls. Astrophotographers, now is your chance to capture scenic photographs by selecting artful and creative foreground objects that look great in silhouette against such a magnificent view.

Venus begins the month in Aries and stands 2.8° northeast of Uranus on April 1. By April 10, it's 3° south of M45 and remains visible after 10 P.M. local time. A telescope reveals a 74-percent-lit disk spanning 15".

Venus passes 8° due north of Aldebaran on April 20; the next night, a crescent Moon joins the scene just below the Pleiades. As darkness falls, the unlit portion of the Moon becomes visible due to earthshine. This phenomenon is a delicate and beautiful enhancement revealing the full disk of the Moon. An observer on the Moon looking back at Earth would see our planet almost fully lit, brighter than the Full Moon on a dark earthly night.

By April 22, the Moon and Venus are less than 7° apart in a glittering scene that includes the Hyades

— Continued on page 34

RISING MOON | The jagged shadow land

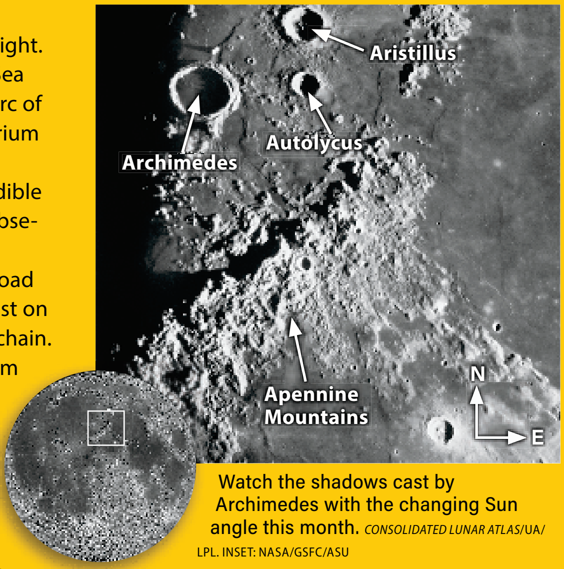
TOWERING TURRETS and chains of pointy peaks span the day-night divide of the First Quarter Moon on March 29. The parade of rugged crater walls continues night after night. In the north, the large, round, undulating Sea of Serenity suddenly gives way to a huge arc of mountains: the outer ring of the Mare Imbrium basin.

The massive impact threw out an incredible amount of material, much of which was subsequently buried when lava floods erupted through the cracked floors. You can see a load of excavated terrain chaotically dumped just on the southeast side of the grand Apennine chain.

Inside the arc lies the attractive oval form of Archimedes. Farther north, in the multiringed Mare Imbrium, look for the remains of an inner wall: It's the large number of isolated yet grouped peaks sprouting out of this Sea of Rains. The long daggers of darkness knifing westward into the terminator shorten with each passing hour of observation and almost disappear in a couple of nights more.

Relive the shadows on April 27. Acting as a canvas, the smooth floor of Archimedes displays the remarkable saw-toothed shadows of the crater rim. But it's all trickery due to the low-angle light from the Sun, which exaggerates apparent height.

Archimedes and the Apennine Mountains



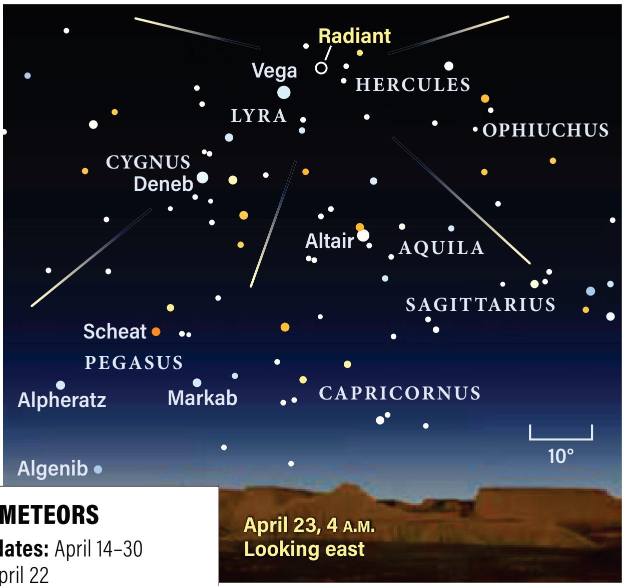
Watch the shadows cast by Archimedes with the changing Sun angle this month. CONSOLIDATED LUNAR ATLAS/UA/LPL. INSET: NASA/GSFC/ASU

At the next sunrise or sunset around your home, try finding a smooth garden wall or guardrail: The low-angle light will cast a shadow that makes them appear covered with dangerous spikes.

Reversed light occurs on the 13th. If you're up at 6 A.M., take in the black teeth biting eastward across the lunar soil.

METEOR WATCH | Look to the Lyre

Lyrid meteor shower



The best time to look for Lyrids is overnight on April 22/23. The radiant rises highest before dawn.

LYRID METEORS

Active dates: April 14–30
Peak: April 22
Moon at peak: Waxing crescent
Maximum rate at peak: 18 meteors/hour

THE LYRID METEOR SHOWER, active from April 14 to 30, peaks the evening of April 22 in the U.S. With the Moon out of the way as a slim evening crescent, conditions are ideal for observing this shower with dark skies. In the early morning hours, Lyra climbs to the zenith just before dawn. The radiant is already 35° high at local midnight. Rates will increase as the radiant rises higher in the sky.

The zenithal hourly rate is 18 meteors per hour and the expected observable rate should reach close to this number in the two hours before the onset of morning twilight. Meteors can occur anywhere in the sky, with longer trails most likely at least 30° to 45° away from the radiant in Lyra. Meteors tend to be brighter in the hour before dawn because the relative speeds of Earth and the shower particles are higher.

STAR DOME

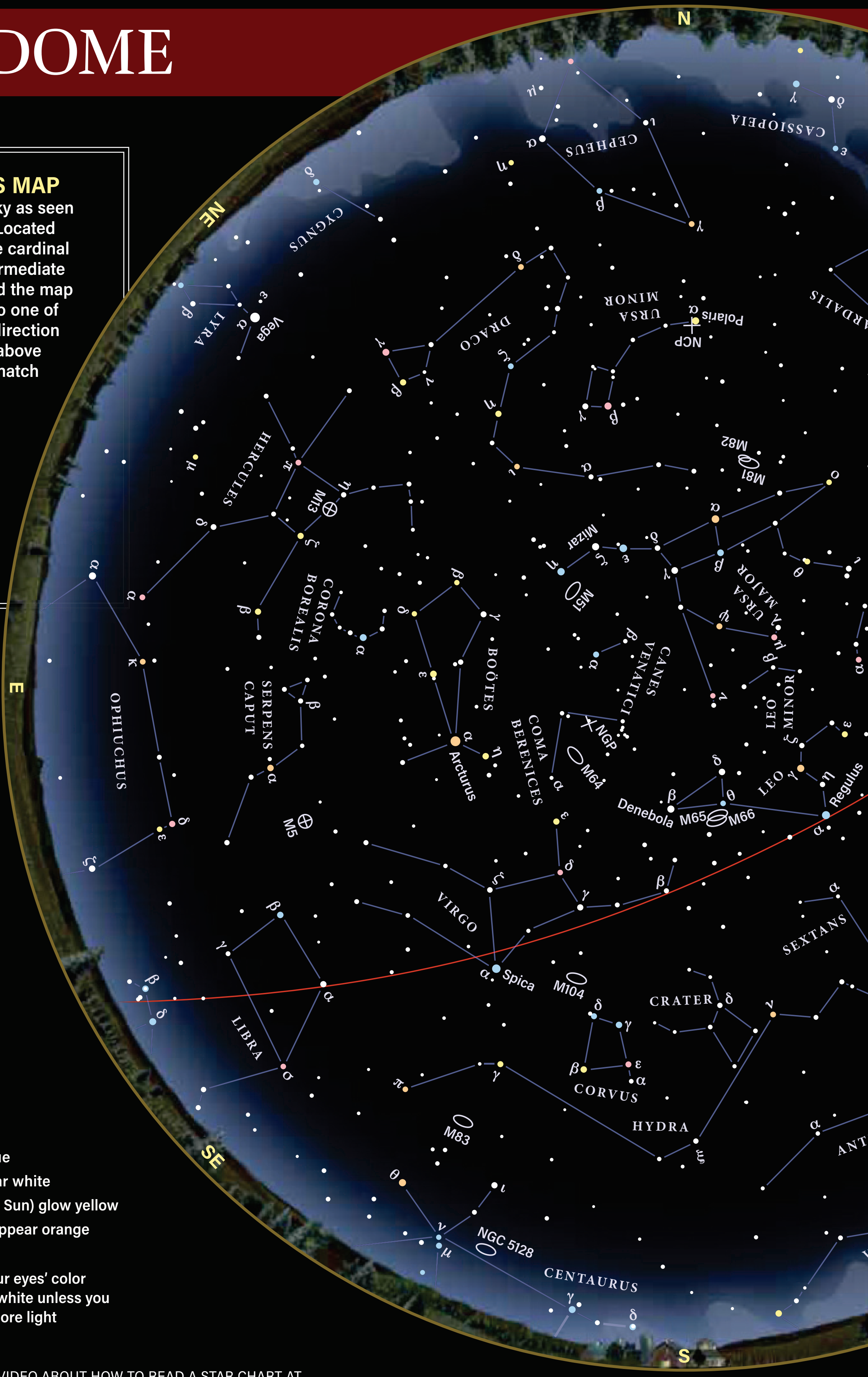
HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

midnight April 1
11 P.M. April 15
10 P.M. April 30

Planets are shown at midmonth



MAP SYMBOLS

- ◌ Open cluster
- ⊕ Globular cluster
- ☐ Diffuse nebula
- ⯐ Planetary nebula
- ⬭ Galaxy

STAR MAGNITUDES

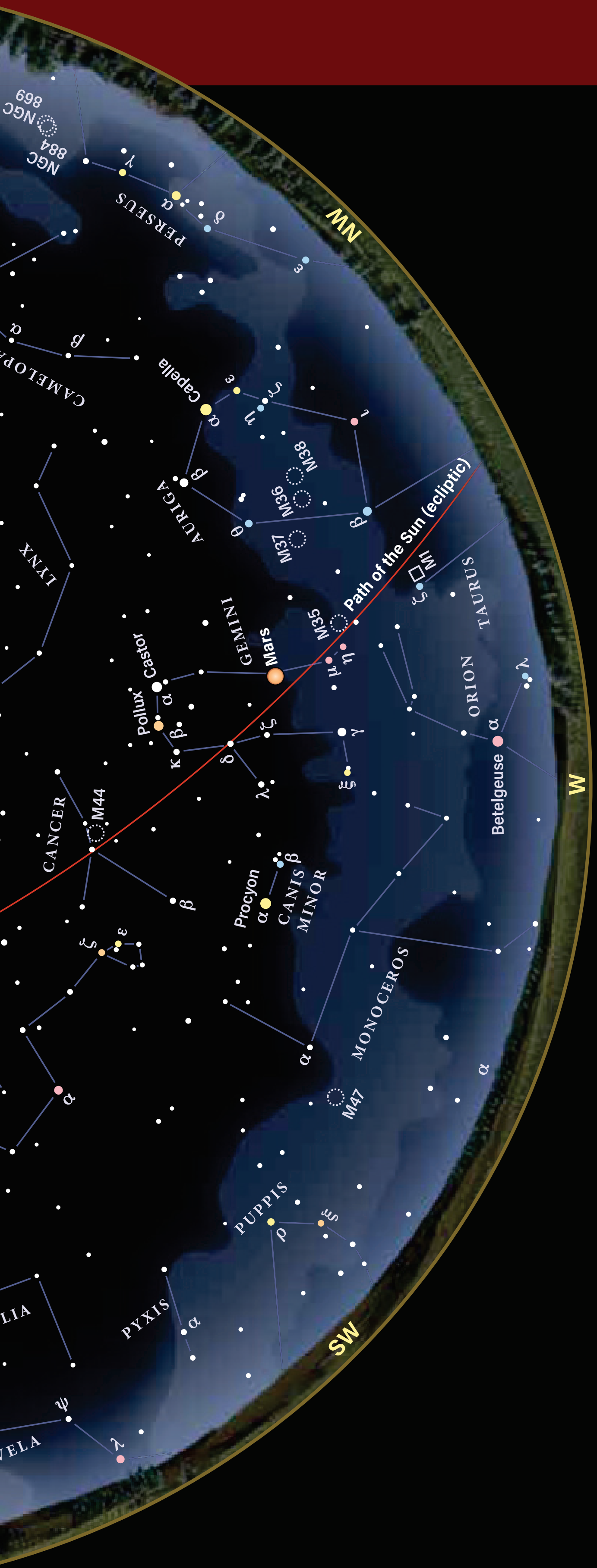
- ● Sirius
- ● 0.0
- • 1.0
- • 2.0
- • 3.0
- · 4.0
- · 5.0

STAR COLORS

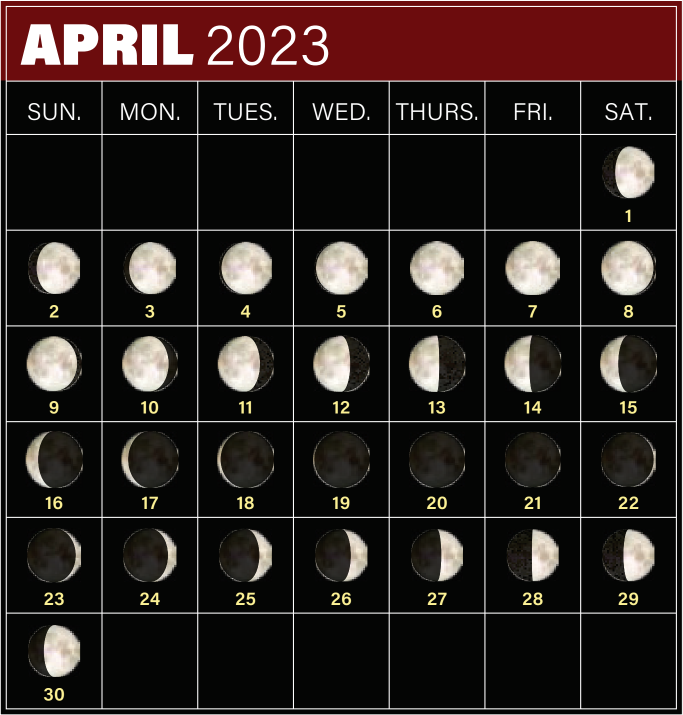
A star's color depends on its surface temperature.

- ■ The hottest stars shine blue
- ■ Slightly cooler stars appear white
- ■ Intermediate stars (like the Sun) glow yellow
- ■ Lower-temperature stars appear orange
- ■ The coolest stars glow red
- ■ Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



APRIL 2023



SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

6 Full Moon occurs at 12:35 A.M. EDT

11 Jupiter is in conjunction with the Sun, 6 P.M. EDT

Mercury is at greatest eastern elongation (19°), 6 P.M. EDT

13 Last Quarter Moon occurs at 5:11 A.M. EDT

15 The Moon is at perigee (228,645 miles from Earth), 10:24 P.M. EDT

The Moon passes 3° south of Saturn, midnight EDT

17 The Moon passes 2° south of Neptune, 1 P.M. EDT

20 New Moon occurs at 12:13 A.M. EDT; hybrid solar eclipse

Venus passes 8° north of Aldebaran, 5 P.M. EDT

21 The Moon passes 1.7° north of Uranus, 9 A.M. EDT

Mercury is stationary, noon EDT

22 Lyrid meteor shower peaks

23 The Moon passes 1.3° north of Venus, 9 A.M. EDT

24 Asteroid Vesta is in conjunction with the Sun, 5 A.M. EDT

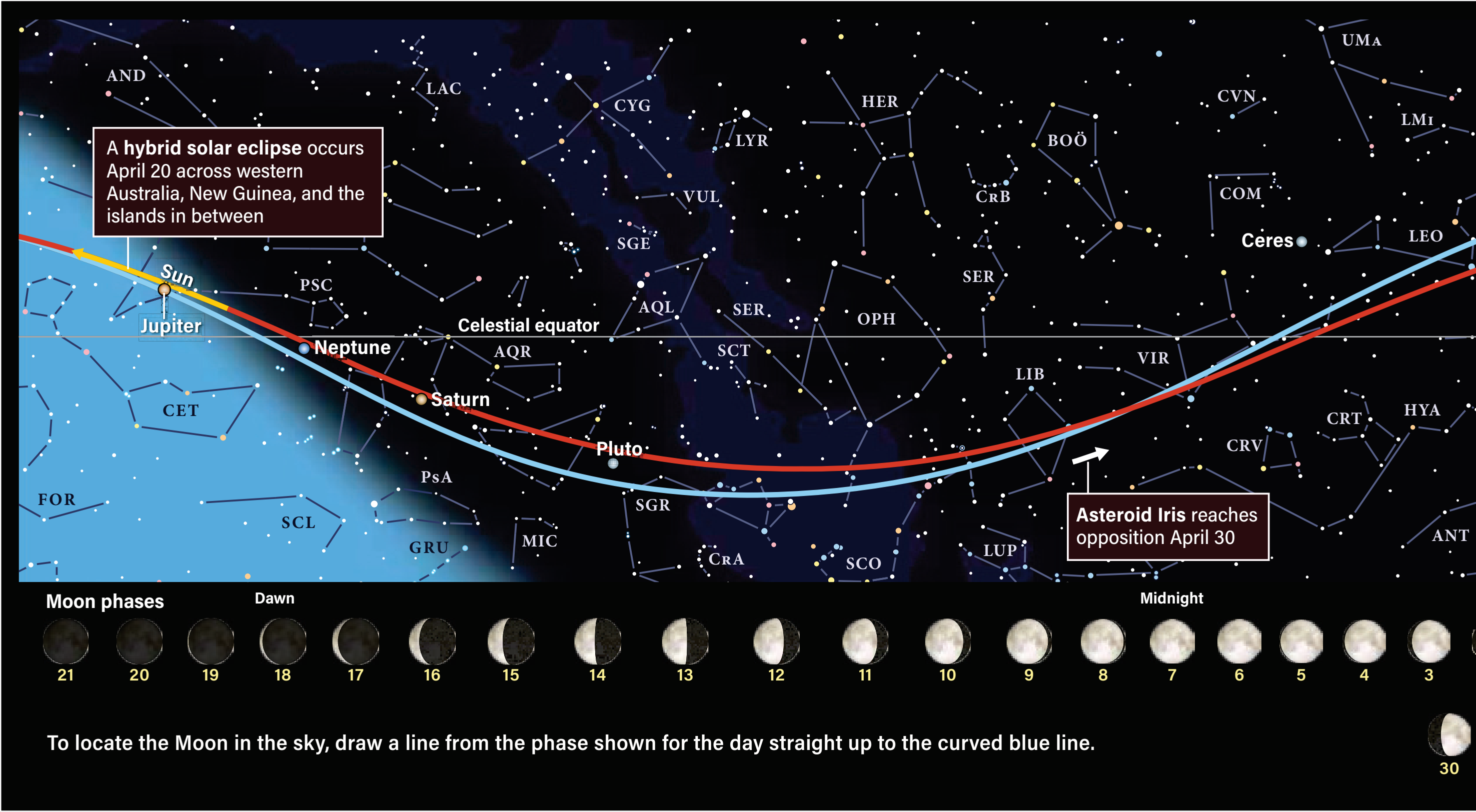
25 The Moon passes 3° north of Mars, 10 P.M. EDT

27 First Quarter Moon occurs at 5:20 P.M. EDT

28 The Moon is at apogee (251,220 miles from Earth), 2:43 A.M. EDT

30 Asteroid Iris is at opposition, noon EDT

PATHS OF THE PLANETS



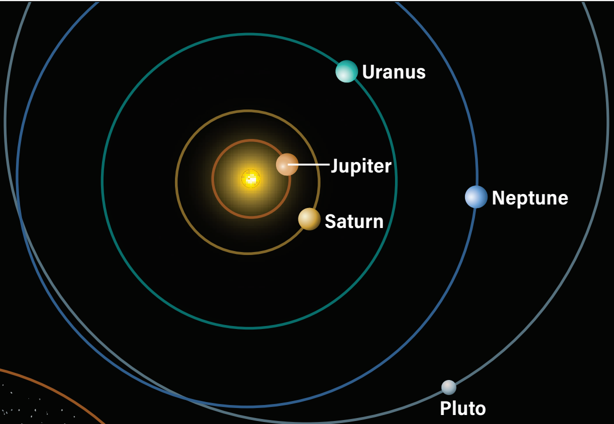
A **hybrid solar eclipse** occurs April 20 across western Australia, New Guinea, and the islands in between

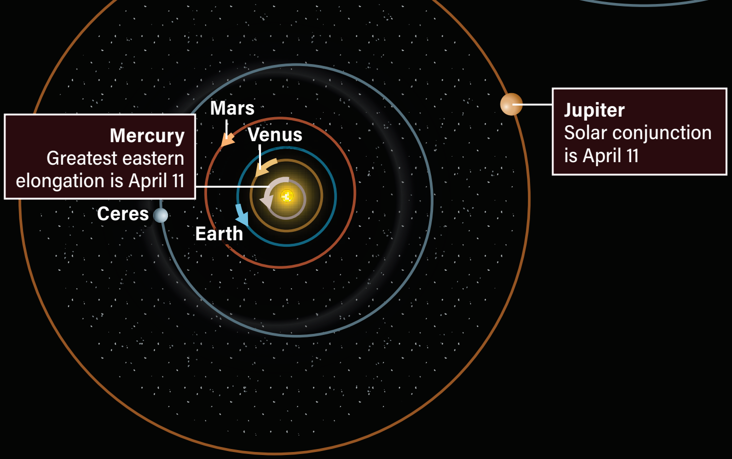
Asteroid Iris reaches opposition April 30

To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.

THE PLANETS IN THEIR ORBITS

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.



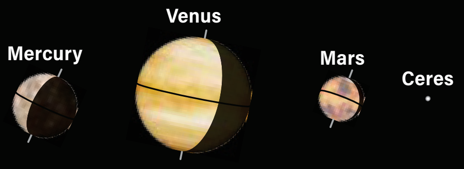


Mercury
Greatest eastern elongation is April 11

Jupiter
Solar conjunction is April 11

THE PLANETS IN THE SKY

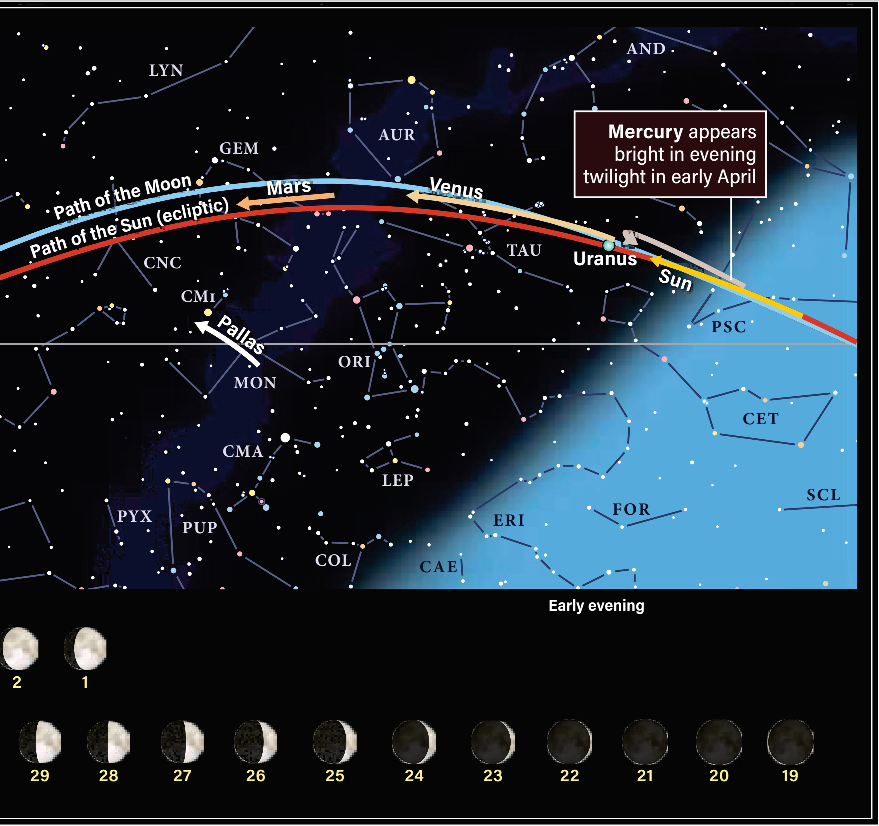
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



PLANETS	MERCURY	VENUS
Date	April 15	April 15
Magnitude	0.5	–4.1
Angular size	8.4"	15.2"
Illumination	29%	73%
Distance (AU) from Earth	0.800	1.098
Distance (AU) from Sun	0.359	0.718
Right ascension (2000.0)	2h39.4m	4h07.1m
Declination (2000.0)	18°37'	22°39'

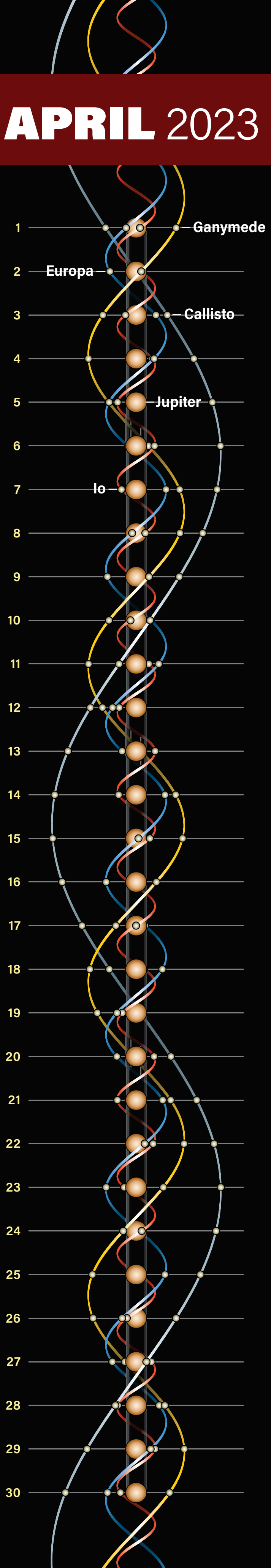
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

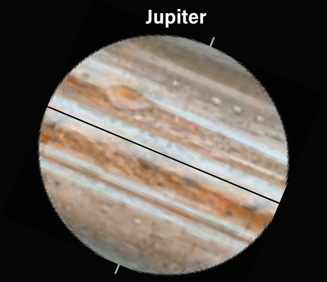
APRIL 2023

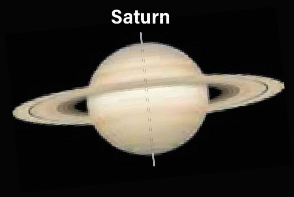


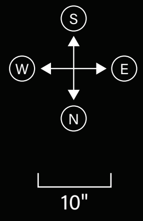
JUPITER'S MOONS

Dots display positions of Galilean satellites at 7 A.M. EDT on the date shown. South is at the top to match the view through a telescope.









MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
April 15	April 15	April 30	April 15	April 15	April 15	April 15
1.1	7.3	–2.1	0.9	5.9	7.8	15.2
5.9"	0.8"	33.3"	16.0"	3.4"	2.2"	0.1"
90%	99%	100%	100%	100%	100%	100%
1.590	1.678	5.928	10.414	20.575	30.787	34.829
1.656	2.578	4.954	9.809	19.654	29.910	34.747
6h44.4m	12h07.9m	1h37.2m	22h24.7m	2h59.4m	23h46.8m	20h10.9m
24°58'	16°22'	8°58'	–11°24'	16°40'	–2°43'	–22°53'

— *Continued from page 29*

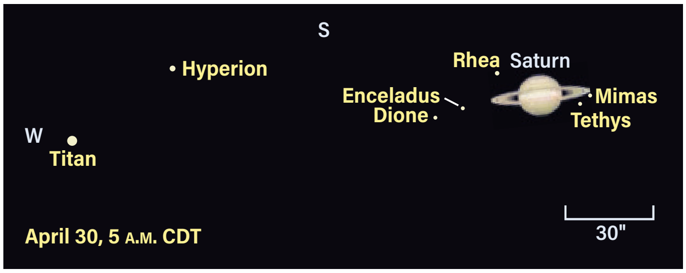
WHEN TO VIEW THE PLANETS

EVENING SKY
Mercury (west)
Venus (west)
Mars (west)
Uranus (west)

MIDNIGHT
Mars (west)

MORNING SKY
Saturn (east)
Neptune (east)

Due west



Titan appears west of Saturn at April's end. Although several moons are shown, some (Mimas, Enceladus, Hyperion) may be too faint for moderate instruments. East Coast observers should look an hour earlier; the moons closest to the rings may appear in slightly different locations.

and Pleiades. Don't miss this memorable view. A fatter, nearly four-day-old Moon is less than 6° above Venus on the 23rd. By now, Venus shows off a 69-percent-lit disk and has grown to a span of 16". It has brightened to magnitude –4.1.

Through the end of April, Venus climbs through the fainter regions of Taurus and adds another arcsecond to its girth. It ends the month located almost midway between the two horns of the Bull, Zeta (ζ) and Beta (β) Tauri, reminiscent of the location of Mars back in November 2022. Between April 27 and 28, the inner planet reaches 1.0 astronomical unit (AU; 93 million miles) from Earth. In the following months, that distance will shrink and its disk will grow until Venus reaches inferior conjunction in August.

Mars makes a delightful appearance at the start of April, shining at magnitude 0.9 and standing 2° northeast of the fine open cluster M35 in Gemini the Twins. Grab a pair of binoculars to view this beautiful scene. A pair of 3rd-magnitude stars, Mu (μ) and Eta (η) Geminorum, sit about 3° south of Mars.

The Red Planet continues its sojourn across Gemini, passing very close to the double star Mebsuta (Epsilon [ε] Geminorum) on April 13 and 14 — on the latter date, it lies within a half-Moon's width of the 3rd-magnitude star. Sometimes the Moon or a planet occults this star due to its proximity to the ecliptic. Mars occulted Mebsuta in one such rare event on April 8, 1976, when astronomers precisely measured properties of the planet's atmosphere.

A waxing crescent Moon joins Mars April 25, when the pair are 3° apart. They hang under the watchful eyes of 1st-magnitude Castor and Pollux, which stand about 8° above Mars and the Moon. By the end of April, Mars is 2° north of Wasat (Delta [δ] Geminorum), another of Gemini's double stars. Mars continues increasing its distance from Earth and, by month's end, reaches 1.7 AU (160 million miles) away, resulting in a tiny disk spanning 5". Telescopic observations of its surface features are subsequently very difficult. The planet remains visible above the horizon until well after midnight all month.

5 to 24 **Hybrid eclipses are rare, with an average of 5 to 24 per century — and sometimes even fewer.**

COMET SEARCH | Get on the ball

AS THE WINTER MILKY WAY sets in the evening, so does Comet C/2020 V2 (ZTF), sinking through Triangulum in the northwest. The moonless window for viewing opens on the 8th; with ZTF only 10° high as astronomical darkness sets in, you need to be ready 90 minutes after sunset.

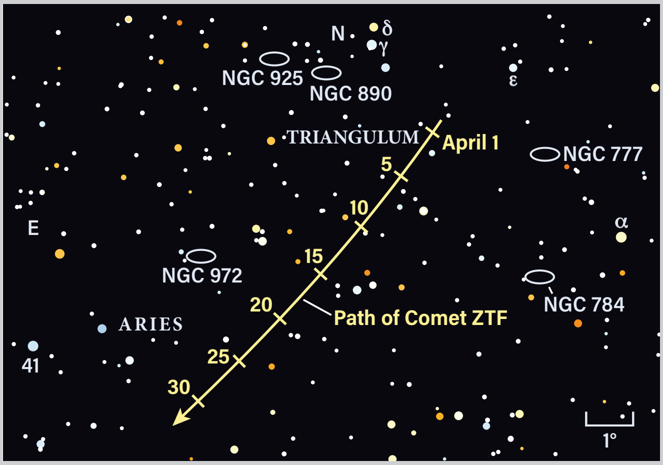
An anti-tail spike is possible from the 21st through the 26th. Imagers with a good stretch of weather can record the transition of the fan-shaped dust tail tilting edge-on, then leaning over to the other side as Earth punches through the comet's orbital plane.

Visual folk need an 8-inch scope well away from city lights to deliver more than a mere glimpse of the small, 10th-magnitude fuzzball. Galaxy NGC 972 provides a comparative target.

ZTF's closest approach to the Sun, perihelion, occurs May 8, but at 2.2 astronomical units, it lies beyond the orbit of Mars — too far for its diatomic carbon molecules to excitedly shine green. (One astronomical unit is the average Earth-Sun distance.)

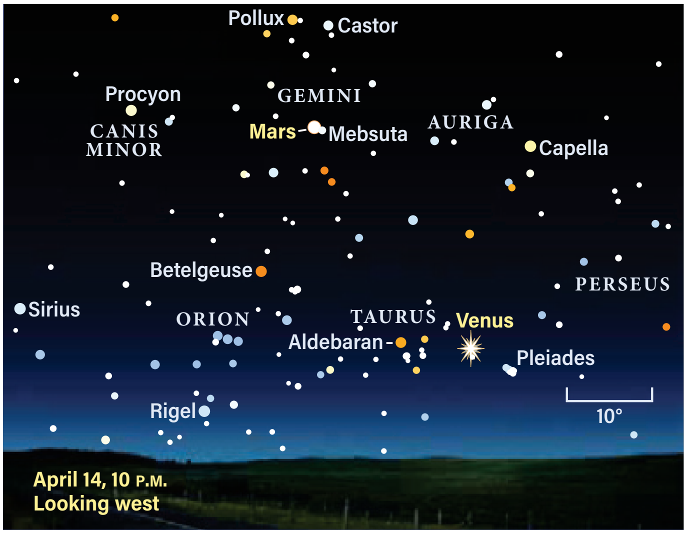
If you're up all night Messier marathoning through the Coma-Virgo Cluster, drop south of the ecliptic in Leo to hunt for C/2019 U5 (PanSTARRS), another faint Oort Cloud sibling masquerading as an isolated galaxy.

Comet C/2020 V2 (ZTF)



Compare C/2020 V2 (ZTF) with the galaxy NGC 972 nearby. You may not see either until you're up at 120x magnification or more.

Meeting Mebsuta



Mars passes within ¼° of Mebsuta in Gemini on April 14. Venus is still visible long after sunset as well.

Saturn rises in Aquarius shortly after 5 A.M. local time on April 1, just as twilight begins. It's a short observation window as the Saturn season opens, but by April 30, things have improved, with Saturn rising two hours earlier and reaching 8° high at the first onset of twilight. It glows at magnitude 0.9, outshining all the stars in this region of sky. A waning crescent Moon hangs 5° below the ringed planet on April 16.

Eager observers swinging a telescope to Saturn low in the sky will be pleasantly rewarded by its 16"-wide disk and a thin set of rings, now inclined by only 9° to our line of sight. They will narrow another couple of degrees as it heads toward an August opposition. In the meantime, enjoy the reappearance of the gas giant in our skies, along with its collection of moons. Titan will be easy to spot late this month, shining at 8th magnitude and due west of Saturn on April 30.

Neptune is just reappearing from behind the Sun in morning twilight. Its magnitude 7.8 disk is poorly placed for observation in Pisces, particularly early in the month. By April 30, it is just 7° high an hour before sunrise.

Jupiter is in conjunction with the Sun April 11 and not visible this month.

This month's April 20 solar eclipse is an unusual "hybrid" eclipse. The eclipse begins and ends as an annular eclipse, but for most of its path, it is total. This occurs because the curvature of Earth causes the Moon's shadow to fall short of reaching the surface for the east and west extremities of the track, where our planet's surface curves away. But the eclipse is total along the central part of the track. Hybrid eclipses are rare, with just five to 24 per century.

April's solar eclipse begins as an annular eclipse at sunrise over the waters of the south Indian Ocean and makes landfall on a tiny promontory of the Cape Range National Park, located 800 miles north of Perth, Australia. Totality lasts some 62 seconds at this remote location.

The moment of greatest eclipse, where totality lasts 1 minute 16 seconds, lies just off the coast of Timor. The track reaches tropical West Papua in the early afternoon, where mountains rise to nearly 10,000 feet and generate lots of weather. The eclipse track briefly visits the island of Biak (65 seconds of totality), which has some developing tourist centers and is the location of a major battle of World War II. The track then races across the Pacific Ocean, turning into an annular eclipse again near sunset, just south of the Marshall Islands.

The next solar eclipse is an annular eclipse on Oct. 14 across the western U.S. and northern South America. It will serve as a preview for the April 8, 2024, total solar eclipse that will cross parts of Mexico, the U.S., and Canada.

Martin Ratcliffe *is a planetarium professional with Evans & Sutherland and enjoys observing from Salt Lake City.* **Alister Ling**, *who lives in Edmonton, Alberta, is a longtime watcher of the skies.*

GET DAILY UPDATES ON YOUR NIGHT SKY AT
www.Astronomy.com/skythisweek.

LOCATING ASTEROIDS

Swing and spot

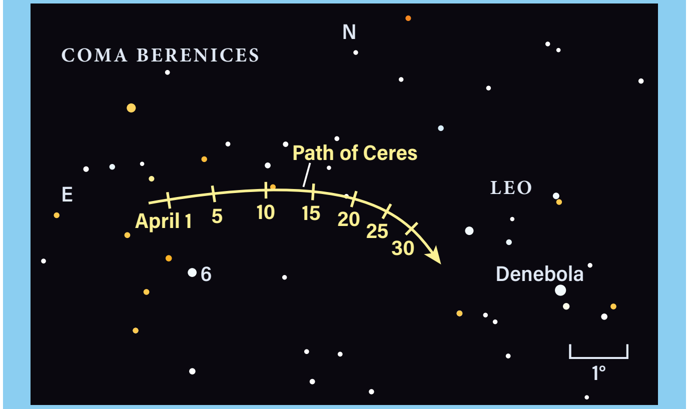
TIME TO BAG AN EASY ASTEROID after a winter of stalking fainter ones. Dwarf planet 1 Ceres is a straightforward binocular catch from the suburbs, just 5° east (left) of Leo's bright tail star, magnitude 2.1 Denebola.

Apart from three or four background stars, Ceres is the brightest dot in view. Use the chart to offset from Denebola and 6 Comae Berenices to orient yourself and peg the correct dot of light — William Herschel was right when he coined the term *asteroid*, Greek for "starlike."

Even experienced observers make mistakes, so to be sure, plot a few stars on a sheet of paper or, better yet, a logbook, and return every few nights to confirm which point has shifted place. Ceres' motion is a challenge to see in one observing session, even in a telescope. Use a triangle of field stars from the 10th to the 12th to reveal the displacement.

Spanning nearly 600 miles, Ceres is ruler of the main belt and massive enough to influence nearby orbits.

Tailgating



Bright Ceres should be easy to find this month swinging past Leo's tail star, Denebola.

ASTRONOMY: ROEN KELLY

Searching for life on WATERY WORLDS

Life within extraterrestrial oceans may not only be possible, it might be flourishing.

BY KLAUS R. BRASCH

HUMANITY HAS LONG LOOKED AT THE STARS and dreamed of what kind of life might exist elsewhere in the universe. In their book *Extraterrestrials: A Field Guide for Earthlings* (Camden House, 1994), popular astronomy author Terence Dickinson and science illustrator Adolf Schaller present a series of alien scenarios in which life as we do and don't know it might exist. Writing at the dawn of exoplanet discovery, the authors speculate on what life might look like on an Earth with lower or higher gravity, with a denser or more tenuous atmosphere, with glacial or jungled surfaces, or as a water world.

When the book was written, the most probable solar system bodies that could potentially host alien life were thought to be Europa and Titan. In the intervening years, our exploration of our solar system with missions like Galileo, Cassini, and New Horizons have revealed that small, icy worlds are more geologically alive than we ever imagined, and subsurface oceans may be common. Ground- and space-based telescopes have also discovered more than 5,000 exoplanetary bodies. Together, these findings have redefined the possibilities for life in our universe.

It is not necessary to find another Earth; any planet that has icy moons could potentially have the right conditions for life to spring forth and flourish.

Two main targets

Jupiter's moon Europa drew much attention with the first flyby images from Pioneers 10 and 11 in the 1970s, and even more with the long-term orbiting Galileo mission beginning in 1995. Europa is one of several worlds in our solar system that host surface or subsurface oceans, along with jovian moons Callisto and Ganymede, saturnian moons Enceladus and Titan, and Pluto. Naturally, these bodies are of major interest not only as potential hosts for life, but also because they are accessible to exploration by space probes and landers.

Experts agree that bodies of this nature typically consist of an icy outer shell covering a water layer atop a silicate or metallic core. For larger satellites like Ganymede, internal pressures are so high that ice at depth may form a "water sandwich," with an ocean located between ice shells.

But on smaller moons like Europa

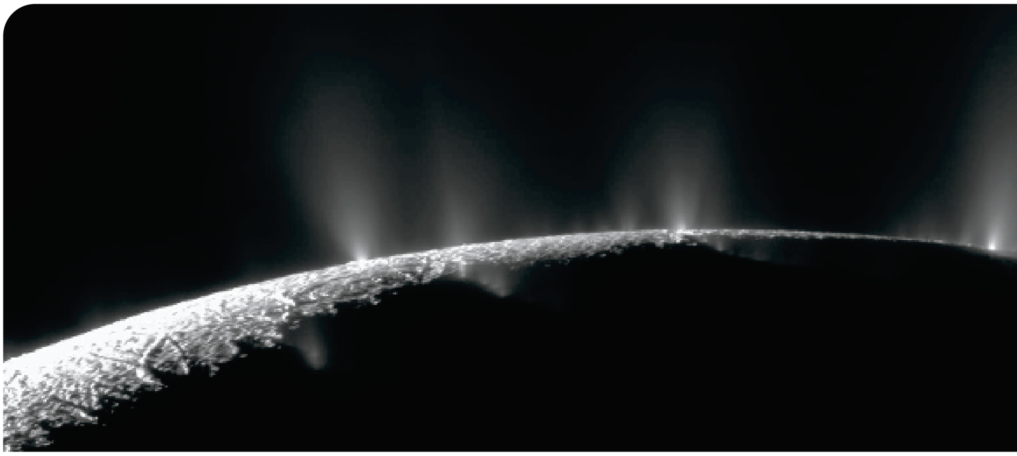
— the smallest of Jupiter's Galilean moons — the ocean likely sits directly above and in contact with the hot, rocky core, which could provide energy for life to develop. Europa's internal composition is likely a silicate mantle and nickel-iron core surrounded by an icy crust covering a 60-mile-deep (100 kilometers) ocean. Tidal friction and flexing due to Jupiter's strong gravitational tug most likely help keep the ocean liquid.

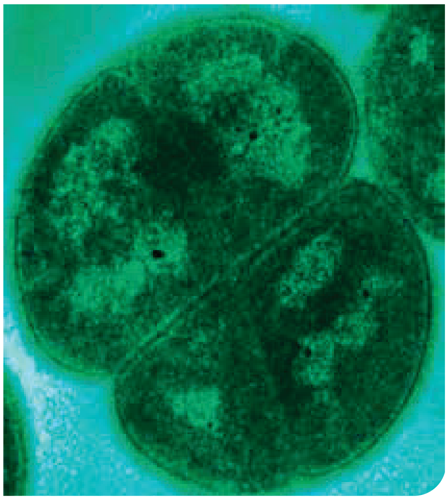
Enceladus is also a strong candidate for a subsurface ocean. Though only some 310 miles (500 km) in diameter and about half the density of Europa, Enceladus is covered with fresh, clean ice. First visited by the Voyager 1 and 2 missions in the 1980s, this moon's unusual nature was fully revealed by the Cassini-Huygens mission to Saturn, which orbited the system from 2004 to 2017. Enceladus is surprisingly free of impact craters, indicating that it continually renews its outer, near-homogeneous white layer of mostly water ice. Long, linear tectonic fractures contain geysers that release water vapor and other gases, strong evidence that a large body of liquid water exists below the crust.

If life has indeed gained a foothold on such worlds, what might it look like and how would it obtain its energy? In their book *Imagined Life* (Smithsonian Books, 2019), authors James Trefil and Michael Summers contemplate two types of ice worlds, which they name Iceheim and Nova Europa.

The first only contains bubbles of liquid water beneath a thick layer of ice, while the latter has a metallic core and rocky mantle surrounded by a deep ocean with a relatively thin ice covering.

Based on current thinking about planetary formation, such worlds may be quite common. Because the only comparable environments on Earth lie deep in our oceans, scientists are studying them to learn what chemical and biological signatures future space probes to Europa and Enceladus should look for.





TOP: The plumes of Enceladus are caused by cryovolcanism, a process that ejects water (rather than molten rock) above the icy moon's surface. NASA

RIGHT: After the discovery of the bacterium *Deinococcus radiodurans* in nuclear reactors, scientists expanded their notions of the types of alien environments in which life could thrive. MICHAEL DALY/WIKIMEDIA COMMONS

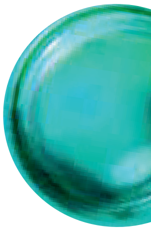
BELOW: Mainly because of the geysers that release vapor into space, the saturnian satellite Enceladus has also become a prime candidate for a subsurface ocean. CASSINI IMAGING TEAM/SSI/JPL/ESA/NASA

Terrestrial analogues

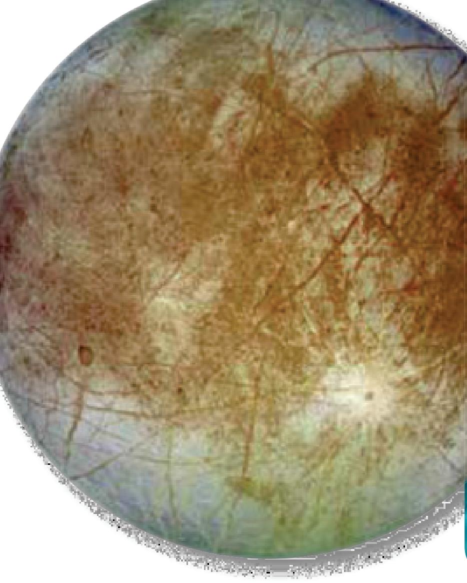
Earth's deepest fissure, the Mariana Trench, despite a total absence of sunlight, is teeming with complex life. Life is also abundant in our midocean ridge system, which wraps around the globe and forms the most extensive arrangement of mountains on the planet. As tectonic plates creep apart there, hydrothermal vents form, gushing warmth and supporting whole communities of organisms.

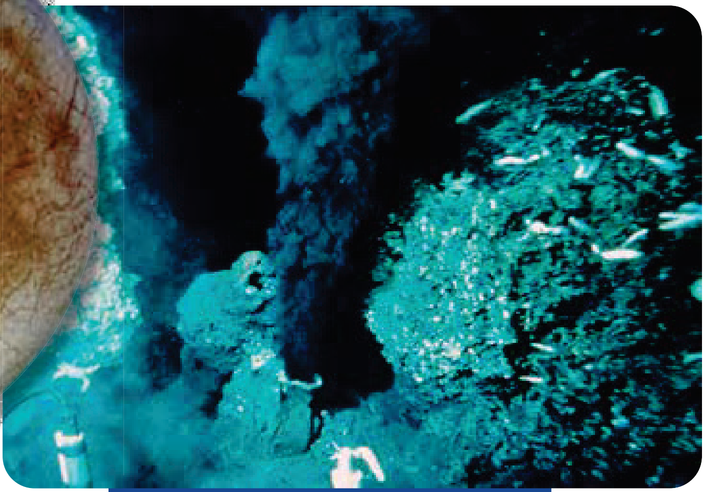
These communities were first directly observed in 1977 during the Galapagos Hydrothermal Expedition, by a team of scientists from several U.S. institutions using deep-sea probes and submersibles. This included the extraordinary crewed submersible *Alvin*, commissioned in 1964 for the Woods Hole Oceanographic Institution and still operational today.

In *Oceanus* magazine, marine geologist Robert Ballard, one of the expedition's scientists, reports, "When they reached their target coordinates, *Alvin* and its three-man crew entered another world." Coming out of small cracks across the lava terrain was warm, shimmering water that rapidly turned cloudy blue as manganese and other chemicals in solution precipitated out and deposited brown stains on the surrounding surface.



"But even more interesting was the presence of a dense biological community living in and around the active vents," Ballard writes. The vents, termed black smokers, result from seawater flowing into the fracture; becoming enriched in different elements; and then expelled as hot (up to 750 degrees Fahrenheit [400 degrees Celsius]), acidic fluids through chimneylike structures. Though it did not garner much public attention at the time, this discovery has





ABOVE: Black smokers are hydrothermal vents that expel extremely hot, mineral-rich water. Many of these vents are hosts to thriving communities of life. W.R. NORMARK/DUDLEY FOSTER/WIKIMEDIA COMMONS

LEFT: Jupiter's moon Europa was one of the first worlds scientists identified as having a subsurface ocean. NASA/JPL

been likened in importance to landing on the Moon.

How did life start?

Exciting as these bio-communities are, it remains unclear how, when, and where they — and life on Earth — originated. It may have been when our oceans first formed; in 2016, Stacey Worman at Duke University and colleagues reported that hydrothermal vent sites contain many of the basic chemical ingredients needed for life, including abiotically (without the presence of life) generated molecular hydrogen, a major energy source for microbes beneath the seafloor. Other energy sources for microorganisms in anoxic (oxygen-free) aquatic environments are the methane and sulfur compounds used by many archaea. (Archaea are thought to be the earliest forms of life on Earth, tracing back at least 3.5 billion years.)

Not surprisingly, such scattered marine bio-communities differ widely across the globe. Does this imply separate origins or simply adaptations to different environments? Probably the latter, due to variations in seafloor topography, tectonic movement, current changes, and inconsistent nutrient availability.

All this shows that life on our planet is amazingly adaptable. For example, many organisms in Arctic and Antarctic environs have evolved a special class of antifreeze proteins that bind to ice crystals, stopping them from further growth and causing fatal cellular damage.

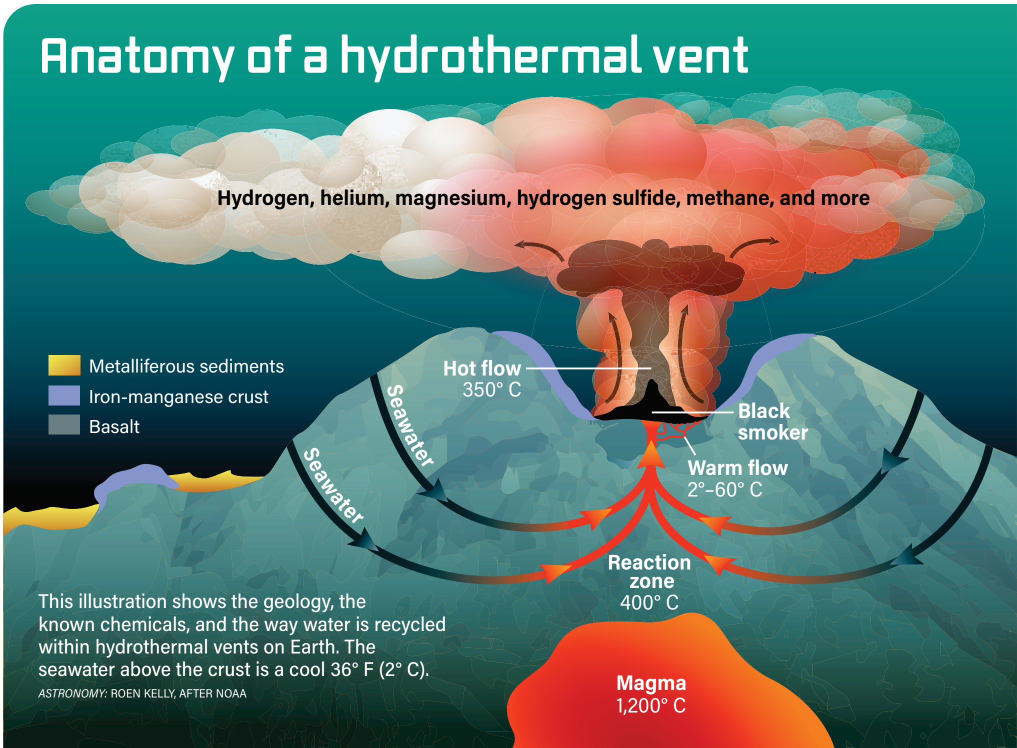
At the other extreme, we find hyperthermophile bacteria in hot springs and deep ocean vents capable of surviving temperatures up to — and past! — the boiling point of water. Undoubtedly the hardiest microbe we know of is the bacterium *Deinococcus radiodurans*, first discovered in tins of meat that had been radiated in an attempt to sterilize them. Not only can it survive cold, dehydration, vacuum, and acid, but it's also the most radiation-resistant organism known, thriving in levels a thousand times higher than humans can tolerate. Such extremophiles reveal that evolution is powerful and raise the question of whether there are limits to this process. Given that terrestrial life has adapted to a wide range of conditions, could alien life be equally malleable?

Alien water life?

Some of the most advanced and intelligent animals today are birds and mammals; among mammals, our closest evolutionary relatives include apes and monkeys, which often exhibit social traits embarrassingly similar to ours.

Perhaps most remarkable though, are cetaceans, including whales, porpoises, and dolphins. Animal behaviorists generally agree that bottlenose dolphins are self-aware and possibly capable of abstract thinking. However, like all mammals, they first evolved on land; only later did they adapt to aquatic environments. So, can truly intelligent animals originate in water?

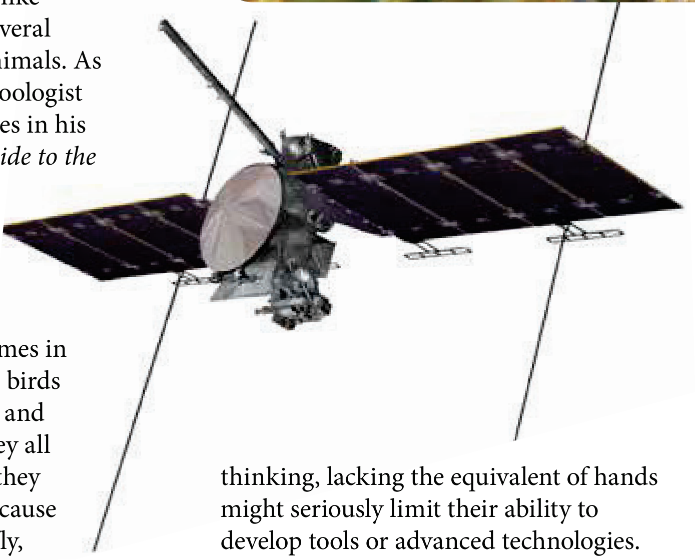
The answer seems to be yes, at least in the case of the remarkably complex octopus. Unlike vertebrates, which have a central brain, these cephalopods have a decentralized system that extends throughout their bodies. In addition to a sizable central brain in their heads, they also possess what might be called



Anatomy of a hydrothermal vent

This illustration shows the geology, the known chemicals, and the way water is recycled within hydrothermal vents on Earth. The seawater above the crust is a cool 36° F (2° C).

ASTRONOMY: ROEN KELLY, AFTER NOAA



ABOVE: Researchers believe the octopus developed in the ocean, rather than starting on land and then moving into a watery environment. Likewise, alien life could develop underground on a world without a solid surface. ALBERT KOK/WIKIMEDIA COMMONS

LEFT: The Europa Clipper spacecraft, scheduled to launch in October 2024, will orbit Jupiter but focus on the giant planet's moon Europa. NASA/JPL/WIKIMEDIA COMMONS

"mini-brains" at the ends of their tentacles. This diversified nervous system allows them to quickly adjust their skin pigmentation to match their physical surroundings, a camouflaging capability useful both for hiding from predators and catching prey. Octopuses also exhibit higher-order cognitive abilities, including problem-solving and even a degree of social interaction with humans.

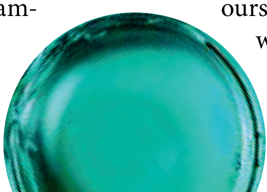
Because they are soft-bodied animals, their evolutionary history is difficult to trace for lack of distinctive fossils. But the nervous systems of these boneless, totally aquatic creatures seems to have evolved in a convergent, almost parallel manner to that of land vertebrates. Perhaps intelligence is a trait that evolution converges on, like wings, which evolved several times in various land animals. As Cambridge University zoologist Arik Kershenbaum writes in his book *The Zoologist's Guide to the Galaxy: What Animals on Earth Reveal About Aliens — and Ourselves* (Penguin, 2021), "On Earth, flight evolved four different times in four different groups: in birds and bats and pterosaurs and insects. The fact that they all use wings isn't because they evolved on Earth; it's because it was advantageous to fly, and wings are just about the only way to fly. And so, we can expect these constraints to be operating everywhere in the universe." The fact that intelligence has evolved multiple times on Earth — on land and in the sea — suggests that it could also happen on alien worlds.

It seems entirely plausible that intelligent, even self-aware beings could evolve over time on alien water worlds. What might such creatures look like: octopuses, dolphins, or humans? Most likely none of these. Rather, they would be creatures unique to their world and its particular physical and chemical environment and life-supporting resources.

It's possible their advancement could be limited due to environmental constraints. Take dolphins, for example. Even if they became math savvy and capable of abstract thinking, lacking the equivalent of hands might seriously limit their ability to develop tools or advanced technologies. Still, it's fun and instructive to speculate, as Trefil and Summers have done, with their fictitious Europa-like world in *Imagined Life*.

Assuming the denizens of Nova Europa evolved appendages to handle things like rocks and shells, might that lead to more complex tools? Lacking fire, they might be able to forge tools from molten rock and metal at ocean vents.

Considering that our first tools were chiseled rocks and flint, leading to axes and spears, who knows how far curiosity and intelligence might propel some intrepid alien octopus over time? What if they eventually made their way through the ice barrier encapsulating their world? Their worldview would undoubtedly undergo a profound change, just as ours did after Copernicus showed we are not the center of the universe.



More data, please

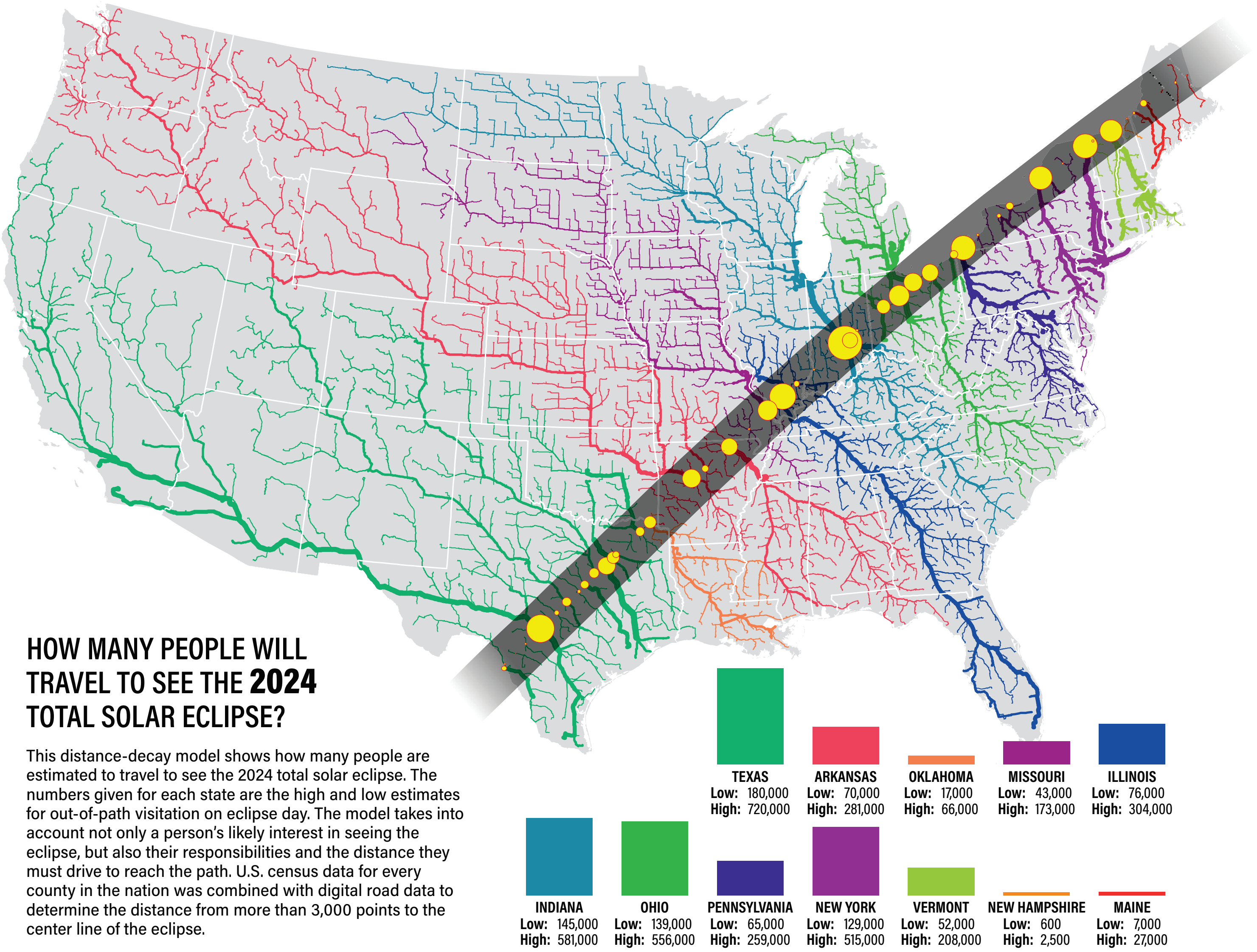
Before speculating further, of course, we must return to hard science. Exciting new steps in that direction will be the European Space Agency's JUpiter ICy moons Explorer (JUICE), slated for launch in 2023, and NASA's Europa Clipper mission in 2024.

JUICE (see page 12) will focus on Ganymede, Callisto, and Europa, Jupiter's three Galilean moons thought to hold significant subsurface bodies of water. Europa Clipper will enter orbit around Jupiter with several planned flybys of Europa and carry instruments to evaluate the moon's potential habitability. In particular, the craft will study Europa's chemical composition and other properties. Future missions are expected to include landers for direct surface exploration.

Clearly, exciting times lie ahead in our quest to find life beyond our home planet and prove whether or not we have company in the universe.

Klaus R. Brasch *is a cellular and molecular biologist with a passion for astroimaging.*

UPCOMING ECLIPSES



HOW MANY PEOPLE WILL TRAVEL TO SEE THE **2024** TOTAL SOLAR ECLIPSE?

This distance-decay model shows how many people are estimated to travel to see the 2024 total solar eclipse. The numbers given for each state are the high and low estimates for out-of-path visitation on eclipse day. The model takes into account not only a person's likely interest in seeing the eclipse, but also their responsibilities and the distance they must drive to reach the path. U.S. census data for every county in the nation was combined with digital road data to determine the distance from more than 3,000 points to the center line of the eclipse.

TEXAS Low: 180,000 High: 720,000
ARKANSAS Low: 70,000 High: 281,000
OKLAHOMA Low: 17,000 High: 66,000
MISSOURI Low: 43,000 High: 173,000
ILLINOIS Low: 76,000 High: 304,000
INDIANA Low: 145,000 High: 581,000
OHIO Low: 139,000 High: 556,000
PENNSYLVANIA Low: 65,000 High: 259,000
NEW YORK Low: 129,000 High: 515,000
VERMONT Low: 52,000 High: 208,000
NEW HAMPSHIRE Low: 600 High: 2,500
MAINE Low: 7,000 High: 27,000

In the next 12 months, an annular and then a total solar eclipse will cross the U.S. Here's where to see them.

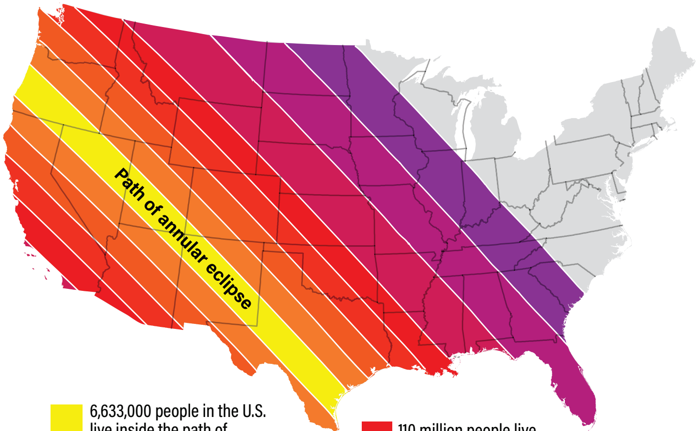
TEXT AND MAPS BY MICHAEL ZEILER

North America will experience two spectacular solar eclipses within a six-month span from Oct. 14, 2023, to April 8, 2024. The first is an annular eclipse whose central path treks across the western U.S. from Oregon to Texas before crossing Central America and northern South America. The second is a total solar eclipse making initial landfall near Mazatlán, Mexico, before sweeping the continent all the way to Newfoundland, Canada. Both are set to once again expose millions to the wonder of eclipses.

These eclipses will also impact our road network, hospitality industry, local medical and police resources, markets and restaurants, and almost every facet of local economies. If you remember the 2017 event, you know how hectic things can get

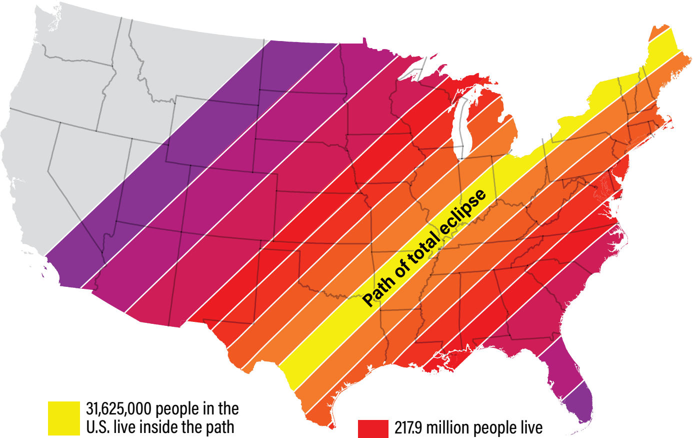
BY THE NUMBERS

HOW MANY PEOPLE LIVE INSIDE AND NEAR THE PATH OF THE **2023** ANNULAR SOLAR ECLIPSE?



- 🟨 6,633,000 people in the U.S. live inside the path of annularity
- 🟧 21.6 million people live within 100 miles
- 🟧 46.8 million people live within 200 miles
- 🟥 80.7 million people live within 300 miles
- 🟥 110 million people live within 400 miles
- 🟥 127 million people live within 600 miles
- 🟪 171 million people live within 800 miles
- 🟪 214 million people live within 1,000 miles

HOW MANY PEOPLE LIVE INSIDE AND NEAR THE PATH OF THE **2024** TOTAL SOLAR ECLIPSE?



- 🟨 31,625,000 people in the U.S. live inside the path of totality
- 🟧 75.3 million people live within 100 miles
- 🟧 149.5 million people live within 200 miles
- 🟥 189.4 million people live within 300 miles
- 🟥 217.9 million people live within 400 miles
- 🟥 239.0 million people live within 600 miles
- 🟪 262.8 million people live within 800 miles
- 🟪 298.5 million people live within 1,000 miles

BOTH MAPS ABOVE: In addition to the millions of people who live in the path of each eclipse, millions more live within just a few hundred miles. Many Americans can experience a total or annular solar eclipse with a simple overnight trip.

before and after eclipses, so if you haven't already started, begin your planning now!

Annular versus total

Let's look at precisely how these upcoming spectacles measure up. During the peak of the annular solar eclipse on Oct. 14, 2023, the Sun will never be completely covered, but will instead appear as a brilliant ring in the sky. The Moon's orbit is slightly elliptical; because our satellite will be near the far end of that orbit in early October, it will appear a bit smaller in diameter than the Sun.

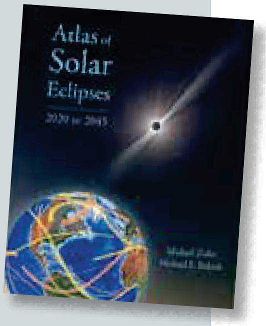
At all times during an annular solar eclipse, you must use solar filters built to the ISO 12312-2 international standard. You can still delight in Baily's beads (the small bits of exposed Sun along the Moon's rough profile), the otherworldly view of the Sun as a perfect ring, the eerie daytime lighting during deep eclipse, and the curved shadow of the Sun projected onto the ground from gaps between tree leaves.

While an annular solar eclipse has its charms, it is merely the opening act for the main attraction: the long-duration total eclipse of the Sun on April 8, 2024. Just 177 days after the 2023 annular eclipse, Mexico, the U.S., and Canada will be split by the 122-mile-wide (197 kilometers) path of a total solar eclipse.

Unlike an annular eclipse, you can safely view totality with your naked eye — but *only* once the Sun has completely moved behind the Moon. During the rest of the event, you must use the same ISO standard 12312-2 solar filter to observe safely.

The 2024 eclipse promises a maximum totality of 4 minutes 28 seconds. During this time, you'll be able to see diamond rings,

SOLAR ECLIPSE ATLAS



Want a closer look at these or other eclipses through the year 2045? *Atlas of Solar Eclipses — 2020 to 2045* by Michael Zeiler and Michael E. Bakich provides maps and key information covering 56 solar eclipses around the world from 2020 to 2045, including the 2023 annular and 2024 total solar eclipses. Within its pages, you'll discover viewing advice, details about the timing of each eclipse and any planets or stars visible during the event, as well as how to select the best viewing location and potential points of interest along the path. Purchase your copy today at www.MyScienceShop.com.

Baily's beads, the Sun's corona, a 360° sunset, and even a few stars and planets.

Heightened interest

The 2017 eclipse left a dramatic impression on millions of Americans, so we can expect high public and media interest in the 2024 eclipse. And this one will be even bigger and better! Consider:

- The 2024 eclipse is nearly twice as long in duration of totality as the 2017 eclipse.

- A total of 31.6 million people in the U.S. already live within the path of totality of the 2024 event. (Only 12 million people lived inside the path of the 2017 eclipse.)

- Major eastern seaboard metropolitan areas such as Washington, D.C., Baltimore, Philadelphia, New York, and Boston are about 200 miles (320 km) from the path of totality, making a short eclipse trip possible for many more millions of people.

ALL EYES ON TEXAS

Both the 2023 and 2024 eclipses will cross the Lone Star State, meaning Texas will be a hotspot of activity for eclipse newbies and veterans. Texas has by far the highest population living inside the paths of both eclipses: 3.8 million in 2023 and 12.8 million in 2024. The state also receives the longest duration of totality in 2024 and annularity in 2023 within the U.S. Plus, for the 2024 eclipse, Texas has the best odds of clear skies in the U.S. for eclipse day. And only New Mexico beats Texas in terms of likely clear weather during the 2023 solar eclipse. *— M.Z.*

Visit **www.Astronomy.com** to read this article with additional maps for both the 2023 and 2024 eclipses.

How many people live inside the eclipse paths?

A total of 6.6 million people live inside the path of the annular solar eclipse of 2023. The three states with the largest population inside the path of the annular solar eclipse are Texas, New Mexico, and Oregon, including the metropolitan areas of San Antonio and Albuquerque. The path also crosses lightly populated areas of California, Nevada, Utah, Arizona, and Colorado, plus a small corner of Idaho.

A total of 31.6 million people in the U.S. live inside the path of totality in 2024. The biggest metropolitan areas are Dallas, San Antonio, Austin, Indianapolis, and Cleveland, and the states with the highest number of residents inside the path are Texas, Ohio, Indiana, and New York.

Getting to totality

In addition to people living in the path of the eclipses, many others will travel to stand under the Moon's shadow. The path of the 2024 eclipse comes near the densely populated metropolitan areas of the American Northeast, the Great Lakes, and Texas. In fact, about half the U.S. population lives within about 250 miles (400 km) of the path of totality! That means half the American population can make an overnight trip to see the eclipse.

At right, the shaded areas around the path of totality indicate drive times in two-hour increments. Bear in mind that this map shows how many hours it will take to drive from your location to the path of the eclipse on a *normal* day. You can generally expect busy but uncongested traffic on the day before or early morning of an eclipse, followed by a sudden traffic jam on the closest highways and freeways the moment the show is over. If you can, plan to spend eclipse night at or near your viewing location.

How many visitors should each state expect?

Many eclipse experts predict that eclipse day will be perhaps

TOP METROPOLITAN AREAS INSIDE THE PATH OF ANNULARITY IN 2023

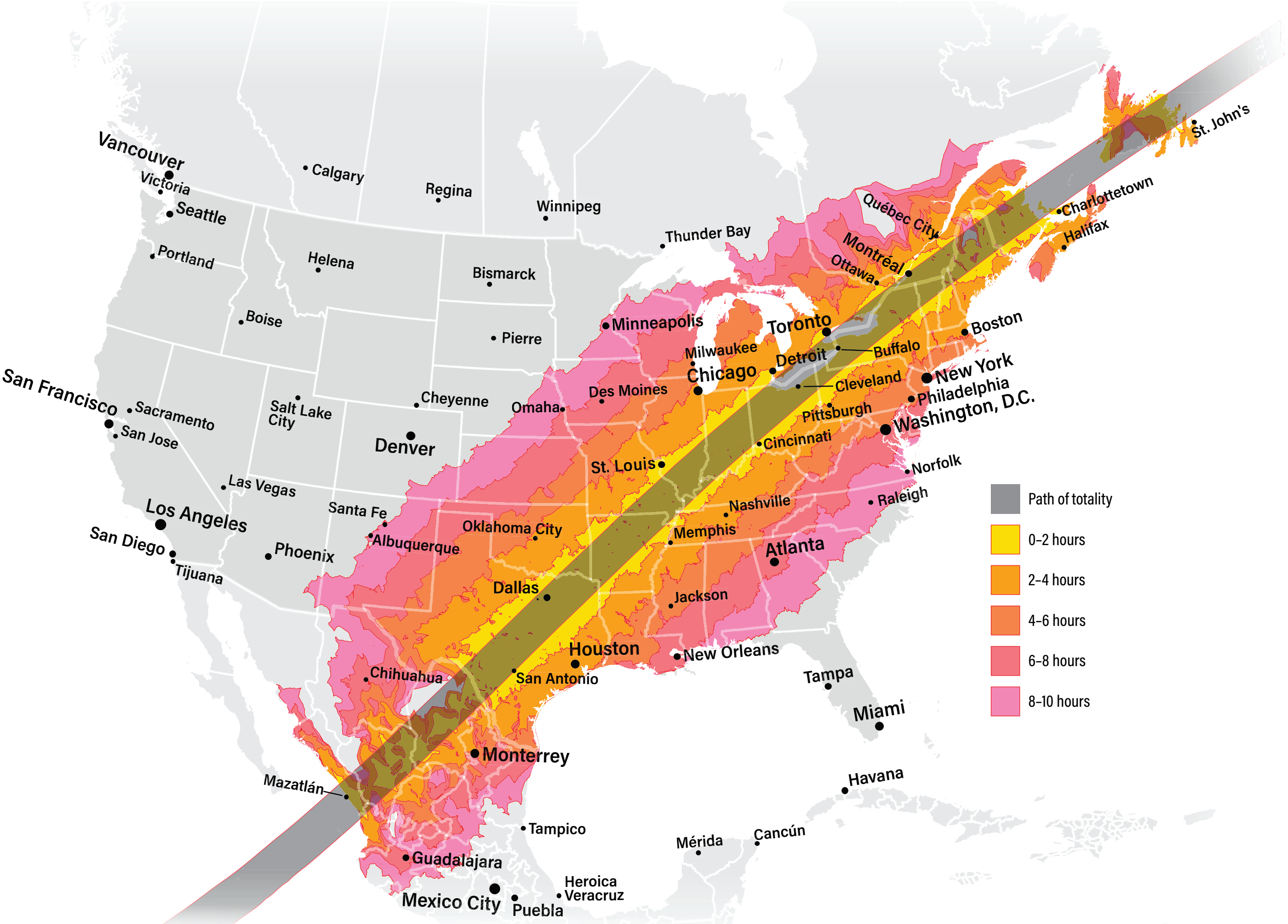
CITY	POPULATION
San Antonio-New Braunfels, Texas*	2,602,000
Albuquerque, New Mexico	921,000
Corpus Christi, Texas	423,000
Eugene-Springfield, Oregon	383,000
Medford, Oregon	224,000
Midland, Texas	172,000
Odessa, Texas	161,000
Santa Fe, New Mexico	155,000
San Angelo, Texas	122,000
Victoria, Texas	101,000

*San Antonio is by far the largest metropolitan area in the path of annularity in 2023.

TOP METROPOLITAN AREAS INSIDE THE PATH OF TOTALITY IN 2024

CITY	POPULATION
Dallas-Fort Worth, Texas*	7,760,000
San Antonio-New Braunfels, Texas	2,602,000
Austin-Round Rock, Texas	2,352,000
Indianapolis-Carmel-Anderson, Indiana	2,129,000
Cleveland-Elyria, Ohio	2,076,000
Buffalo-Niagara Falls, New York	1,162,000
Dayton, Ohio	814,000
Little Rock-North Little Rock-Conway, Arkansas	750,000
Akron, Ohio	700,000
Toledo, Ohio	644,000

*The Dallas-Fort Worth metropolitan area includes nearly two-thirds of Texas residents inside the path of totality in 2024.



HOW LONG DOES IT TAKE TO DRIVE TO THE PATH OF TOTALITY IN **2024**?

This shaded map shows the drive time, broken into two-hour increments, to reach the path of totality during the 2024 eclipse. Note this is only for pre-eclipse drive times to reach the path on a normal day.

the largest national gathering in the history of the U.S. Can't quite believe it? Let's look at the numbers.

I developed an eclipse visitation distance-decay model that starts with the simple and obvious observation that the closer someone is to the path of totality, the more likely they are to go see the eclipse. I used this model to predict travel patterns for the 2017 eclipse and it proved broadly correct (though Wyoming far exceeded my prediction).

For the 2024 total solar eclipse, I estimate 923,000 to 2,077,000 people will travel to the path of totality. Of these, Texas gets a plurality of 180,000 to 720,000 visitors, followed by Indiana, Ohio, and New York. What is remarkable about the path of totality is the proximity to the major metropolitan areas of the northeastern U.S. Philadelphia, Baltimore, New York, Washington, D.C., and Boston are only about 200 miles (322 km) from the path. Indeed, more than half the U.S. population is within 250 miles (400 km) of the path of totality! And these estimates exclude people already living in the eclipse path, so add about 31.6 million people for the 2024 total solar eclipse.

REUSING YOUR ECLIPSE GLASSES

To check whether your eclipse glasses from the 2023 annular event are still good for 2024, shine an LED flashlight against the lens. You should see only a dim light source. Also check the lenses for any signs of scratches, tears, or holes — discard them if there is any damage, no matter how superficial it may appear. *—M.Z.*

R. GINO SANTA MARIA/SHUTTERFREE, LLC/DREAMSTIME

The impacts of the eclipses

The streams of visitors to view the 2023 and 2024 eclipses will impact many communities around the country. But the greatest impact will be the immeasurable beauty of viewing the Sun in a whole new way.

The Sun is a giant, dynamic magnet and the coronal swirls, loops, and streamers visible only during a total solar eclipse reveal the imprint of its intense magnetic fields. It is this fleeting glimpse of our star that makes total solar eclipses so special to all who see them, and worth traveling hundreds of miles to see.

Michael Zeiler *is a longtime eclipse chaser and retired cartographer. He and his wife Polly White operate the website www.greatamericaneclipse.com, a leading source of maps and information about upcoming eclipses.*

Stars have been completely omitted from this narrowband image of the Statue of Liberty Nebula (NGC 3576) to feature its nebulosity. ALL IMAGES: WARREN KELLER

ERASING STARS with AI tools

Change up your astroimaging routine with starless skyscapes.

BY WARREN KELLER

ONE OF THE IRONIES of deep-sky imaging is that stars are generally not the stars of the show. Of course, there are exceptions with targets like open clusters. But for nebulae and other objects, the presence of these bright points of light in an image can hinder an astroimager from teasing out details.

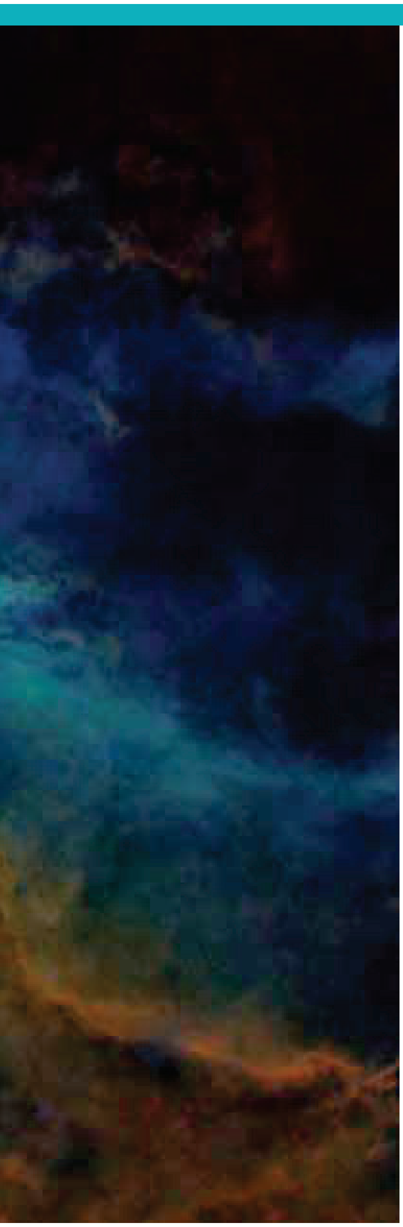
Image-processing programs like PixInsight by Pleiades Astrophoto and Adobe Photoshop have offered methods to remove stars from images — but they can be labor intensive and yield mixed results. Two new, cutting-edge tools make it much easier.

The programs StarNet and StarXTerminator were developed independently, but both use a form of artificial intelligence (AI): neural networks trained to recognize stars and remove them from astroimages. The freeware StarNet can be used within PixInsight or as a standalone tool; StarXTerminator can be used as a plug-in with PixInsight and Photoshop, but requires users to purchase a license.

After using them, the target objects in your image can be manipulated without concern for those pesky stars. When processing is complete, the stars can easily be placed back into the image if the imager desires. Or, the stars can be left out for a dramatic display of isolated nebulosity — an especially popular look with narrowband images.

The problem

For an astroimager, stars present unique challenges. While faint deep-sky objects benefit from long exposures, brighter stars can quickly saturate a sensor, resulting in colorless and unnatural-looking orbs. You may find that a good compromise is taking shorter exposures, but more of them.



The same issue rears its head when processing an image. When a raw image file is imported to your computer, it is in a linear state, meaning that the brightness values from pixel to pixel are the same as when they were recorded by the camera. This typically yields a dark-looking image with little contrast. The pixel values must be nonlinearly stretched (brightened) to reveal what's hiding in its initial linear state. Because many stars are already bright, stretching the dimmer parts of an image can damage the stars in the same way as overexposing them, and care should be taken to avoid this.

Because stars can't be stretched far — and also because they don't require the same amount of attention and processing as the faint, delicate features of a nebula — one approach to dealing with them is to mask them out. This is like a housepainter using tape to shield areas from a new color. Likewise, applying a virtual mask to an image protects specific elements (e.g., stars) so that adjustments such as noise reduction and sharpening don't adversely affect them.

While masks do this rather well, making them takes time and requires some level of expertise to get them right. It's easy to overlook objects or introduce unwanted artifacts. And while PixInsight, the dedicated astroimage-processing program, has built-in capabilities to create a star mask, the more general-purpose Photoshop does not. But thanks to the power of neural networks, StarNet and StarXTerminator make star removal as easy as clicking a button.

StarNet

StarNet began its life in 2019 as a script called StarNet++ written for PixInsight by Nikita Misiura. It was featured in PixInsight's Script menu, which contains many free third-party plug-ins. While the original version did a commendable job of removing stars, it took a rather long time to run and left some star artifacts behind.

Despite these minor shortcomings, PixInsight's developer, Pleiades Astrophoto, embraced the tool. The company converted the plug-in from JavaScript to C++, the same language as PixInsight's main processes, and incorporated it as a native tool in the main Process menu, where it is now called StarNet.

The primary reason for the less-than-perfect performance from StarNet++'s original algorithm was a lack of training of the neural network. The key to machine learning is training algorithms on vast, varied quantities of data. The appearance of stars can vary greatly in brightness and shape, including halos and diffraction spikes. While the human brain knows that all these variants are stars, a neural network must be taught to recognize them.

Misiura's original algorithm was trained using only data taken with his modest imaging system. And when he first released StarNet++, he was completing postdoctoral work in data science, leaving little time for improving the program. In early 2022, however, Misiura released StarNet2, a vastly improved version of the original process. (At the time of this writing, it has not yet replaced StarNet 1.0 in the PixInsight general release, but should be included in a future revision.)

While it's recommended that stars be removed early in the workflow, I usually make some basic corrections to the data before applying StarNet2.

A representative workflow might include the elimination of light gradients, color correction, linear noise reduction, delinearization (nonlinear stretching), and a touch more noise reduction after the stretch. In PixInsight, tools to accomplish these tasks might be DynamicBackground Extraction, ColorCalibration, MultiscaleLinearTransform, MaskedStretch, and TGVDenoise, respectively.

At the top of page 46, (1) shows a splendid image of the R Coronae Australis region processed to the point where stars are ready to be removed.

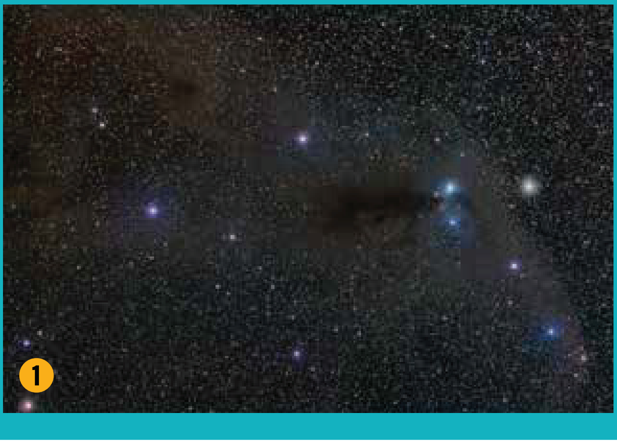
When processing data from a color camera (one-shot color, DSLR, or mirrorless), it is ideal to first apply a touch of color saturation with CurvesTransformation and then run StarNet2. If working with monochromatic data that includes luminance, it makes sense to wait until the luminance data have been combined with the color image using LRGBCombination — in this way, star removal need only be done once.

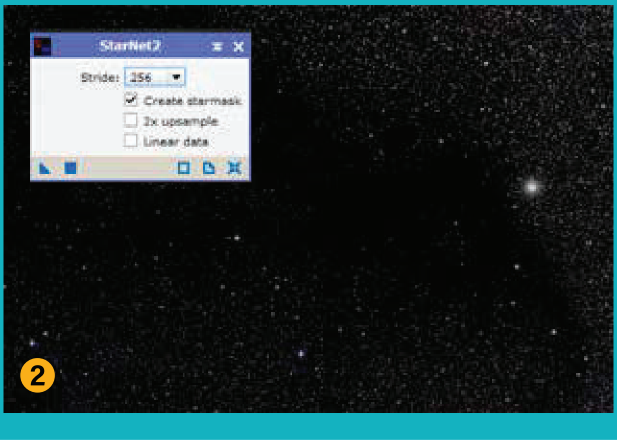
StarNet2's interface is simple but has a few options. Leave the Stride setting at the default of 256. If you intend to replace the stars after processing the starless image, choose "Create starmask." This is a bit of a misnomer — the image produced isn't a mask at all, but rather the stars themselves, shown in (2).

Misiura states that some "tight and bright" stars can produce artifacts, and the "2x upsample" option, which upsamples the image before star removal, is designed to

StarNet2
is available for free at www.starnetastro.com and can be installed to the current version of PixInsight. There is also a standalone version that can be run from a command line or graphical user interface on Windows, MacOS, and Linux.

HOW TO SEPARATE STARS FROM IMAGES IN PIXINSIGHT





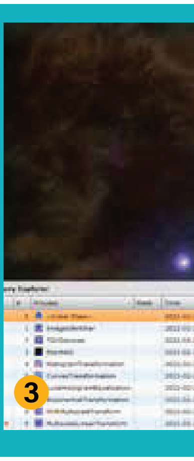
StarNet2

Stride: 256

☑ Create starmask

☐ 2x upsample

☐ Linear data



alleviate them. In my tests, I felt this was unnecessary.

I don't recommend using the last option, "Linear data." This internally delinearizes a linear image, then removes the stars before unstretching the image back again. Best practice is to use an image that has already been delinearized with MaskedStretch, as described above, or with HistogramTransformation.

After running the plug-in and isolating the nebulosity, you can massage fine details via PixInsight's full array of tools with no risk of blowing out the stars.

Image (3) above demonstrates how well StarNet2 performs on an image filled with thousands of tiny stars. The result has also been enhanced with the processes visible in the History Explorer: HistogramTransformation and ExponentialTransformation to brighten the image, CurvesTransformation for enhancing color saturation, LocalHistogramEqualization for boosting contrast, MultiscaleLinearTransform for sharpening, and HDRMultiscaleTransform for bringing out the detail in the cores of the nebula by compressing their brightness. Of course, there is rarely one way of skinning the proverbial cat, and a similar result could be achieved with a different mix of available tools.

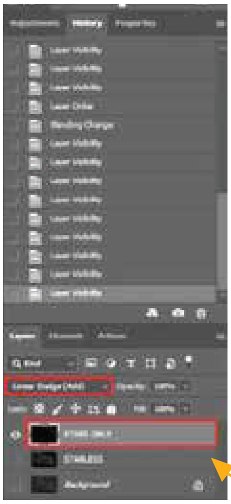
Once you are satisfied with the development of the nebula, it is time to replace the stars. You can also make mild adjustments to the image that contains the stars — like tweaking color saturation — before reuniting it with the main image. Using the settings shown in (4), apply PixelMath to the starless image if you wish to put the stars back in. You could also try reducing the star contribution by multiplying the star-mask image by a number less than 1 (e.g., starless + 0.75*star_mask).

StarXTerminator

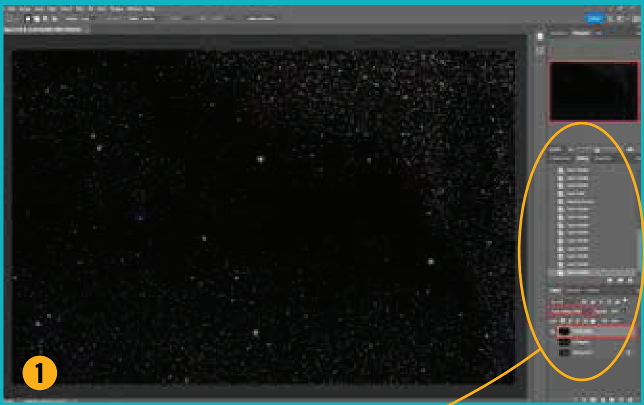
As StarNet2 is free and does a great job, imagers whose main workflow is in PixInsight may not need anything more for star removal. However, for imagers who prefer working in Photoshop, Russell Croman of RC Astro offers an attractive solution in the payware tool StarXTerminator. (StarXTerminator does also work with PixInsight.)

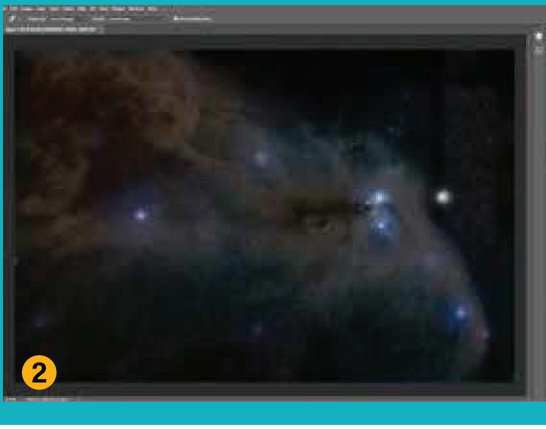
A highly accomplished silicon chip designer, Croman has been involved in astrophotography for decades as an imager and author of some very useful Photoshop plug-ins, like GradientXTerminator and StarShrink.

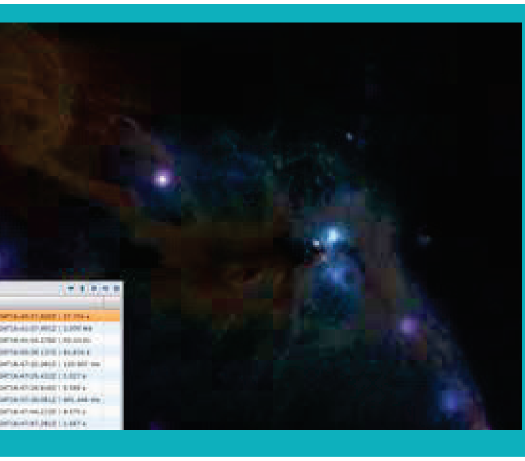
StarXTerminator debuted in September 2021 and picked up where StarNet 1.0 left off, using its own unique neural network and a variety of training data that Croman had produced with different imaging systems over his decades in the hobby. As a result, StarXTerminator's star-removing ability is superior to the original version of StarNet

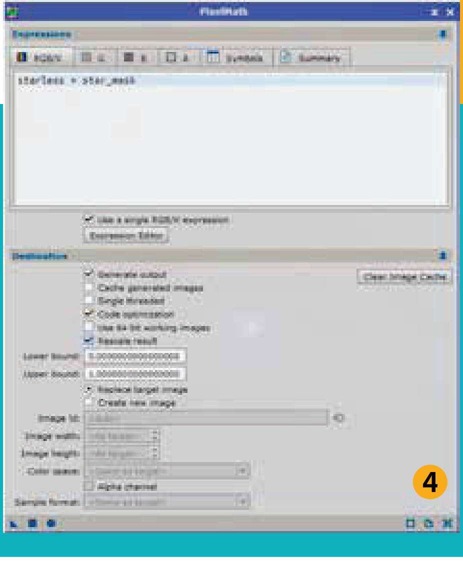


HOW TO SEPARATE STARS FROM IMAGES IN PHOTOSHOP









starless + star_mask

1 The R Coronae Australis complex is one of the closest star-forming regions, at a distance of only 420 light-years. It features delicate reflection and dark nebulae that are easier to process with stars removed.

2 StarNet2 does an impressive job of isolating stars. The "starmask" image that StarNet2 produces is not a mask, but the stars themselves. The options box is at upper left.

3 The starless image can be processed without fear of damaging stars.

4 Use these options to recombine the stars with the starless image. Try experimenting with different factors for the stars image.

and on par with StarNet2. Some extended stellar elements such as large halos may be better handled by one or the other utility, but overall, both tools perform brilliantly.

After purchasing or downloading the free trial of StarXTerminator, the files must be placed in Photoshop's Plug-ins folder per the instructions in the included PDF file. After opening the plug-in within Photoshop's Filter menu and entering the license key sent by email, you'll need to download the latest version of the neural network by clicking "Download AI." With each revision, the neural network is trained further with data from different optical systems, making the program better at recognizing stars of all shapes and sizes and preventing damage to nonstellar structures. As of this writing, version 11 has been released, trained on a dataset including images from the Hubble and James Webb space telescopes.

If you intend for your final image to be starless, using StarXTerminator in Photoshop couldn't be simpler — just apply the tool directly to the image. However, if you intend to blend the stars back in later, you can generate a Photoshop project with isolated stars and nebulosity in just a few steps.

As Photoshop cannot open FITS files or PixInsight's XISF format, begin with a 16-bit TIFF file. Start processing by duplicating the background layer twice. From the Filter menu, run StarXTerminator on the top layer. Duplicate this layer, then make the duplicate invisible by toggling its tiny eyeball icon. Set the lower, original starless layer's blend mode to Subtract, then merge this layer with the one below it using the keyboard command Ctrl+E or the Merge Down command in the Layers panel menu. This is now the layer containing the stars alone. Drag it to the top and set the blend mode to "Linear Dodge (add)."

You should now have three layers, as shown below in (1): the original photograph (bottom), the starless version (middle), and the stars themselves (top). To work on the starless layer, activate it by clicking on it and be sure that the eyeball icon is on. You may wish to temporarily turn off the star layer to better see what you're doing (2).

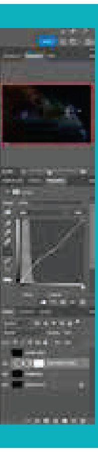
With stars out of the picture, the nebula or galaxy in the middle layer can be enhanced in a variety of ways. In (2), a Curves adjustment is applied to significantly boost the nebula's brightness and contrast. When processing is complete, you can flatten the layers. Whether to include the stars — as in (3) — or not is your choice!

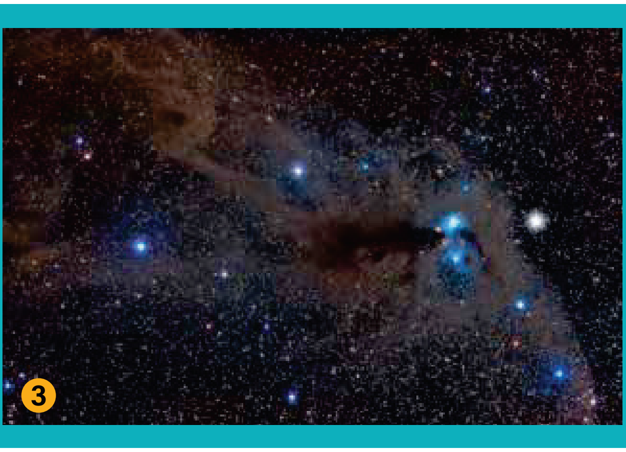
The techniques outlined here harness the power of AI, yet leave all the creative decisions in your hands. Even if the dramatic look of starless skyscapes does not appeal to you, these star-removal tools can give you much more control over your final images.

Warren Keller *is a world-renowned astroimager and teacher of image-processing who has written extensively on the subject.*

StarXTerminator

is available as a plug-in for PixInsight and Photoshop for $59.95. Its universal license key works for Windows, MacOS, and Linux operating systems. A free 30-day trial is available at www.rc-astro.com/resources/StarXTerminator.





1 After running StarXTerminator in Photoshop to generate a starless layer, you can produce the inverse — a layer with only the stars — by blending a duplicate starless layer in subtraction mode with the original background layer.

2 You can then turn the stars layer on or off with the visibility toggle in the Layers panel. A simple curves adjustment to boost the shadows can enhance the nebula's detail.

3 Being able to process the stars and the nebula separately can yield spectacular results.

WE TEST

Celestron's 10-inch StarSense Explorer

This scope uses your smartphone to put thousands of deep-sky objects at your fingertips. **BY MICHAEL E. BAKICH**

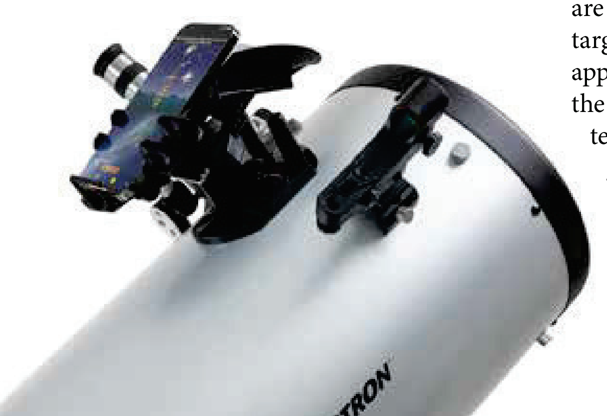
PERHAPS NOTHING HAS revolutionized amateur astronomy more than go-to telescopes with motorized drives that find and track any of thousands of deep-sky objects. No longer must users rely on a celestial map to star-hop to the wonders of the sky. Some models, however, have proven a bit too complicated for beginners — and, as the scopes' sizes increase to access ever-fainter objects, they've proven a bit too expensive as well.

But the engineers at Celestron have hit upon a novel approach: The company's recent StarSense Explorer line drops the motorized drive and puts the software and the database into our smartphones.

Once the author set up the StarSense Explorer, his first target was the Ring Nebula (M57). The app put it in the center of the field of view. DON GOLDMAN

Meet the StarSense Explorers

Celestron has several models in its line of StarSense Explorer telescopes, first introduced May 2021. They include 3.1-inch and 4-inch refractors, 4.5-inch and 5.1-inch reflectors, and a 5-inch Schmidt-Cassegrain. The company also has just introduced 8-inch and 10-inch Dobsonian models.



The technology differs from Celestron's StarSense AutoAlign add-on accessory. Once you attach an AutoAlign unit to a Celestron go-to scope, it uses a digital camera to take a series of images of the night sky. The built-in database then plate solves the images for recognizable star patterns and calculates where the telescope is pointed.

Instead, the StarSense Explorer models are "push-to" models. After selecting a target with the free Celestron StarSense app, the observer follows the arrows on the phone's screen, manually moving the telescope until the bull's-eye turns green. The target is then ready to view in the eyepiece. The StarSense Explorer telescopes substitute a motorized go-to mount for your smartphone's GPS and camera, which is precisely aimed at a tilted mirror, to plate solve. At first glance, that may seem like a step backward — after all, you have to manually adjust the telescope. But it actually serves two purposes: making the cosmos accessible and teaching beginners how to find objects in the night sky.

The free StarSense app is compatible with iOS and Android devices. It works with the iPhone 6 and newer and on Android phones manufactured in 2016 or later, as long as they run at least Android 7.1.2. The phone must have a built-in camera, gyroscope, and accelerometer.

It's here

The scope arrived securely packaged in two boxes. Inside one was the optical tube assembly. The other contained the flat parts of the Dobsonian mount and lots of Allen head bolts to connect everything together. The package also contained a box of accessories that included the smartphone dock, a red-dot finder so you could point to an object by eye, an eyepiece rack, the base handle, and an instruction manual. I received a 25mm Omni Plössl eyepiece, a 2" focuser extension tube, and a 2"-to-1¼" eyepiece adapter.

One nice feature Celestron included was a 2-inch (5.1 centimeters) knob that sits 2 inches (5.1 cm) high, pre-attached to the tube. Grabbing this made moving the scope around easier than using the front end of the tube.

The adjustable dock held my

PRODUCT INFORMATION

StarSense Explorer 10" Dobsonian
Type: Newtonian reflector
Aperture: 10 inches (254 mm)
Focal length: 1,200mm
Focal ratio: f/4.7
Focuser: 2" Crayford focuser
Tube length: 44 inches (111.8 cm)
Tube weight: 29.2 pounds (13.24 kg)
Base dimensions: 26.5 by 21 by 21 inches (67.3 by 53.3 by 53.3 cm)
Base weight: 25.6 pounds (11.6 kg)
Price: $1,099.95
Contact: Celestron
2835 Columbia St.
Torrance, CA 90503
310.328.9560
www.celestron.com

Celestron's StarSense Explorer Dob uses an easy-to-learn "push-to" technology to locate celestial objects. CELESTRON

reasonably large Android phone and case securely no matter where I pointed the telescope. Once your phone is locked in, you need to center it to the dock's tilted mirror. (The tilt is set at the factory.) The StarSense app has easy-to-follow instructions on how to do this, but basically, you just turn the dock's two adjustment screws until your camera is unobstructed.

The fine alignment begins when you point your telescope at an earthly object at least 100 yards (100 meters) away. It could be the top of a utility pole, a street sign, the top of a tree, etc. Center the object first in the red-dot finder, then in the scope's eyepiece. Zoom in your phone's view and slide it around with your finger until the same object is centered on the crosshairs. You may also need to use the dock's adjustment screws until you center the target.

The app recommends practicing this during the day so you're prepared to do it at night. I recommend aligning the scope around the middle of evening twilight. Alternatively, the next best option is to center your scope and phone on one of the cusps (points) of the crescent Moon.

Time to observe

The app uses a "planetarium" view to display the sky, complete with star and constellation names, lines showing each constellation's outline, planets, and select deep-sky objects. When you're ready to observe something, just tap it. If you're not sure what to look at, hit the Star icon for a list of "best objects." Pick one! A box with its name will appear at the bottom. Select it, and you'll see information about the object.

On the screen you'll see arrows and a bull's-eye. The former tell you which direction to move the scope, while the latter shows where the scope is pointing. If you're not anywhere close to the object, the bull's-eye will be red. As you adjust the scope, stop every few seconds so the app can recognize some stars; once you're close enough, the bull's-eye will turn yellow. Finally, when you're on target, it will turn green.

Because I was testing a 10-inch scope under a dark sky, I headed for the deep sky. My first selection was the Ring Nebula (M57) in Lyra. Here's where amateurs usually cross their fingers and hope they're centered — it's a big sky and it can be incredibly easy to get lost when you start out. But my first thought was, "Celestron's got this." And, indeed, when I looked through the eyepiece, there was the evanescent doughnut of the famous Ring.

I didn't have to venture far to target M57, so next I wanted to seek out an object that required more of a telescopic trek. I selected the Sombrero Galaxy (M104) in Virgo, nearly 100° from the Ring. Grabbing the handle, I slowly moved the scope southwest. When the bull's-eye turned green, I looked in the eyepiece, and there it was.

I spent the night finding and viewing another 15 or so objects — all of which fell at or near the center of the eyepiece's field of view — and I had a blast. The app was easy to use and, aside from a few gentle nudges while observing — especially with higher-power eyepieces (remember this system does not track) — everything was straightforward. Overall, I'd say nothing I did was complicated enough to intimidate a novice observer.

And that's not even mentioning the telescope itself. After all, Celestron's 10-inch Dobsonian is the heart of this setup. Unsurprisingly, it provided great views! Celestron is a well-known brand for a reason, and the StarSense Explorer more than lived up to their reputation.

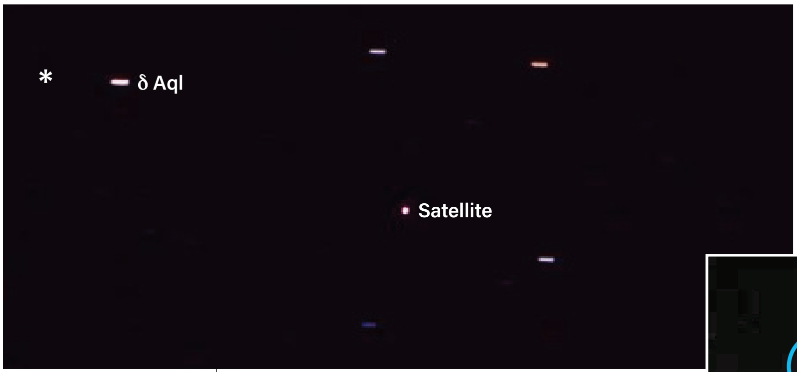
My verdict: The StarSense Explorer 10" Dobsonian is a hit. Its two-piece construction makes it easy to set up or transport, it features a worthy aperture with high-quality optics, and the push-to system is easy to understand, align, and use.

Whether you buy the 10-inch or a smaller model, you can expect a great experience under the starry sky.

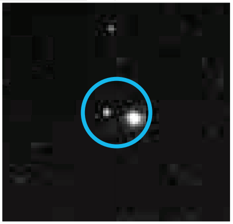
Michael E. Bakich *is a contributing editor of* Astronomy *who lives under a fairly dark sky in Tucson.*

Scanning the sky

Learning about your environment will help you pick out new phenomena.



ABOVE: The author took this 200mm telephoto view of a naked-eye geostationary satellite glint Sept. 17, 2022. The asterisk marks the position of the satellite the previous night. Note how the satellite remains stationary while the stars drift in this 13-second unguided exposure. STEPHEN JAMES O'MEARA



RIGHT CENTER: Peter Meadows recorded this 2nd-magnitude glint from a Superbird B1 communications satellite some 22,500 miles (36,200 km) high at 21h58m UT, Feb. 22, 2022. The bright star in the blue circle is Betelgeuse in Orion; the glint is just to its left. PETER MEADOWS

BY STEPHEN JAMES O'MEARA

Stephen is a globe-trotting observer who is always looking for the next great celestial event.

In a 1952 *Journal of Criminal Law and Criminology* article titled "Importance of Observation in Law Enforcement," Raymond A. Dahl, then director of the Police Training School of the Milwaukee Police Department, encouraged officers to improve their observational faculties by constantly exercising them, and to fix details in mind until a scene becomes familiar. Observers can help themselves, Dahl wrote, by asking, "What attracted my attention?" He added, "Constant repetition is the only way to perfection."

Dahl's advice applies equally well to visual astronomy. Repeat observations in our own visual patrols are the steppingstones to boosting confidence levels and chances for good fortune.

Take, for instance, English astronomer George Alcock (1912–2000), the pioneering visual nova hunter who spent thousands of hours familiarizing himself with some 30,000 stars in the Milky Way. This baseline knowledge allowed him to discover five novae with naked-eye observations from 1967 to 1991.

> "Constant repetition is the only way to perfection."

Familiarizing ourselves with the night sky can also open our eyes to other fantastic phenomena. Case in point: On the evening of Sept. 16, 2022, my wife Deborah and I were relaxing on our deck in Maun, Botswana. Around 7:11 P.M., about four minutes into the start of astronomical twilight, I looked up to Aquila the Eagle, only to rub my eyes in disbelief. Just a few arcminutes northwest of 3rd-magnitude Delta (δ) Aquilae shone a 4th-magnitude celestial "stranger," to use the words of Alcock.

I waited about 30 seconds. When the star did not appear to move, I dashed inside and grabbed a pair of 8x42 binoculars. Given that Aquila lies in a rich swath of Milky Way, my thoughts turned to novae. The binocular view revealed the "new star" shining with a bold orange hue. Wanting to share the view with Deborah, I handed her the binoculars. But to my dismay, the object was gone. I was devastated.

I could only guess that what I saw was a flash from an extremely high-orbiting satellite. I had observed such satellites before, but only dimly through a telescope. Some online research quickly revealed that several observers have seen or imaged these events. One remarkable instance occurred the night of Feb. 22/23, 2022, when Peter Meadows of Chelmsford, England, recorded a 2nd-magnitude flare from a bright geosynchronous satellite near Betelgeuse in Orion. His investigation revealed that it was light reflecting off solar panels from a Superbird B1 communications satellite.

After reading about Meadows' capture, I went out again the following night and, indeed, spied the culprit around the same time, farther east of Delta. I also imaged the satellite appearing to slip eastward against the stars as the Earth rotated — a telltale sign of either a geostationary or geosynchronous satellite.

Geostationary and geosynchronous satellites vary in size, from about that of a watermelon to that of a pickup truck. Since they orbit some 22,200 miles (35,800 kilometers) high (or about 100 times farther than the International Space Station), seeing a glint from them seems almost impossible. Yet, as the evidence shows, under the right conditions — namely, around opposition — a satellite's solar panels can cause Sun glints bright enough to be seen without optical aid. From my latitude (roughly 20° south), geostationary satellites lie about 3° north of the celestial equator; the fact that the satellite I observed was next to Delta Aquilae (declination of +3°) confirms this suspicion.

The purpose of this column, however, is not so much to get you excited about the possibility of seeing a nova or a geostationary satellite, but to inspire you to make constant visual sweeps of the night sky, which might just open your eyes to new wonders. As the journalist Loudon Wainwright wrote in the Nov. 24, 1967, issue of *Life* magazine about Alcock and his passion for the stars, "The key to discoveries like Alcock's is great familiarization with the sky." Or, as Dahl says, "Experience … will be of value only if you continually try to improve your own ability."

As always, feel free to share what has opened your eyes to the sky at sjomeara31@gmail.com.

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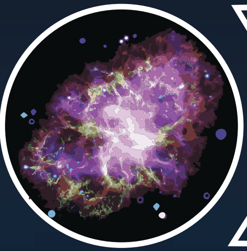

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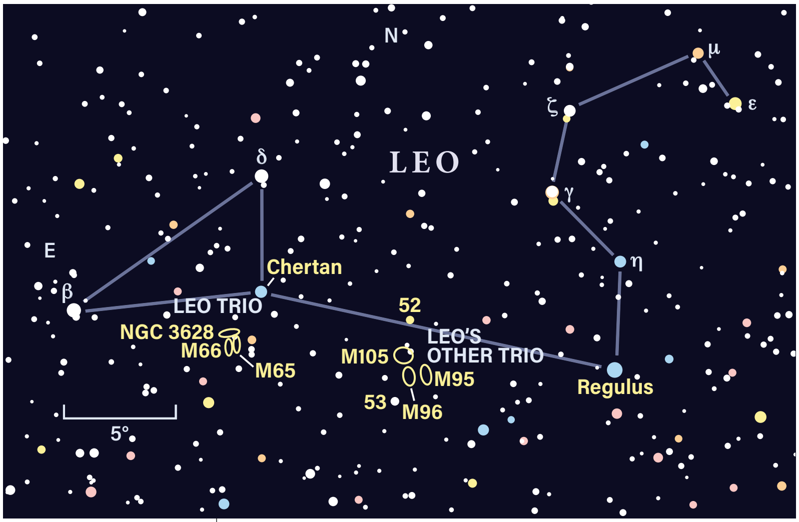
Leo’s other trio

Get the lion’s share with these three proximate galaxies.



Like the Leo Triplet, Leo’s Other Trio encompasses three close-set galaxies in the Lion. *ASTRONOMY:* ROEN KELLY

BY PHIL HARRINGTON

Phil received the Walter Scott Houston Award at Stellafane 2018 for his lifelong work promoting and teaching astronomy.

Leo the Lion is one of the oldest constellations, with origins dating back to the Mesopotamians. It is also one of the most distinctive constellations in the night sky. Brilliant Regulus, marking Leo’s heart, first calls our attention. The Lion’s regal silhouette is created from an asterism forming a question mark or sickle, which marks its head. The rest of the seated body extends eastward toward its triangular hindquarters and tail.

Leo sits in an area rich in distant galaxies. Most are too faint to be visible through binoculars, but a few are bright enough to tempt us to give them a go. We visited three that lie in the same field of view — M65, M66, and NGC 3628 — in this column back in April 2018. Collectively, those are nicknamed the Leo Triplet or Leo Trio. This month, we are back to ferret out three other close-set galaxies, which I call **Leo’s Other Trio**.

All three challenge binoculars even with a sky that is both clear and dark.

These galaxies — M95, M96, and M105 — are believed to be about 35 million light-years away, according to NASA scientists. That’s about 2 million light-years farther than the original Leo Trio.

Both M95 and M96 were discovered by Pierre Méchain on March 20, 1781. Charles Messier confirmed them four nights later, describing M95 as a “nebula without star,” adding, “Its light is very faint.” As for M96, he also saw it as a “nebula without star” and indicated, “This one is less distinct.”

Although M105 is only ¾° north of M96, Méchain didn’t bump into it until March 24, 1781. While M95 and M96 were added to the Messier catalog quickly, M105 was not. Some believe that Messier may not have had enough time to corroborate Méchain’s discovery before his catalog went to press. It wasn’t added until 1947, after U.S.-born Canadian astronomer Helen Sawyer Hogg uncovered a letter written by Méchain describing the galaxy.

Like the original Leo Triplet, M95, M96, and M105 are easy to locate: Aim about halfway along the Lion’s belly between Regulus (Alpha [α] Leonis) and Chertan (Theta [θ] Leonis). There, you’ll find 5th-magnitude 52 Leonis. Place it near the top of the field and another 5th-magnitude star, 53 Leonis, will pop into the bottom. Hold those stars in place and the three galaxies are centered in the field — even though you may not realize it at first.

That’s because while they are easy to locate, they are not easy to see; all three challenge binoculars even with a sky that is both clear and dark. But with perseverance and a little strategy, I have spotted them through my 10x50 binoculars. And if I can see them, so can you.

First try your luck with **M96**, which shines at magnitude 9.2. Although Messier thought it was fainter than M95, it strikes me and others as slightly brighter. From my suburban backyard, my tripod-mounted 10x50 binoculars show a small, slightly oval glow that brightens toward the center. Switching to my 16x70s increases its visibility but adds little detail. Photographs reveal a tightly wound type Sa spiral galaxy that is seen almost face-on from our vantage point.

Those 16x70s also help bring out barred spiral **M95**, which lies just ¾° to the west. M95 is about half a magnitude fainter than M96. My 10x50s uncover only a faint, slightly fuzzy “star,” while the 16x70s add evidence of its disk. In photos, M95 looks like Darth Vader’s starship from *Star Wars: A New Hope*. The central nucleus serves as the spherical cockpit, while the straight bar extends to spiral arms that form a pair of curved wings.

M105 completes the triad. M105 is a type E1 elliptical that shows little structural detail through even the largest telescopes. Despite this bland appearance, M105 is believed to be a massive galaxy. You’ll find its round disk just southeast of the 7th-magnitude star HD 93273. Some observers feel that M105 is brighter than M96, while others find the opposite to be true.

Finally, if you own large binoculars, give M105’s neighbor a try. **NGC 3384** is less than 10' northeast of M105. At only 11th magnitude, it’s sure to be a tough catch.

I would love to hear how you made out with these challenging targets. Drop me a line through my website, philharrington.net. Until next month, remember that two eyes are better than one.

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INDEX *of* ADVERTISERS

AP Grzegorz Popławski 2
Bob's Knobs 53
Box of Tricks Ltd 27
Celestron 60
Chiracahua Sky Village LLC 53
Daniel R. Spirer Jewelers, LLC 5
Dream Telescopes 53
Eclipse Traveler 6
Heritage Auctioneers & Galleries, Inc. 59
iOptron 5
Lowell Observatory 5
Metamorphosis Jewelry Design 5
NEAF DEALER PAGE 60
Northeast Astronomy Forum 27
Oberwerk 53
Precise Parts 53
Rainbow Symphony 53
Scope Buggy 5
Space and Beyond Box 51
Technical Innovations 5

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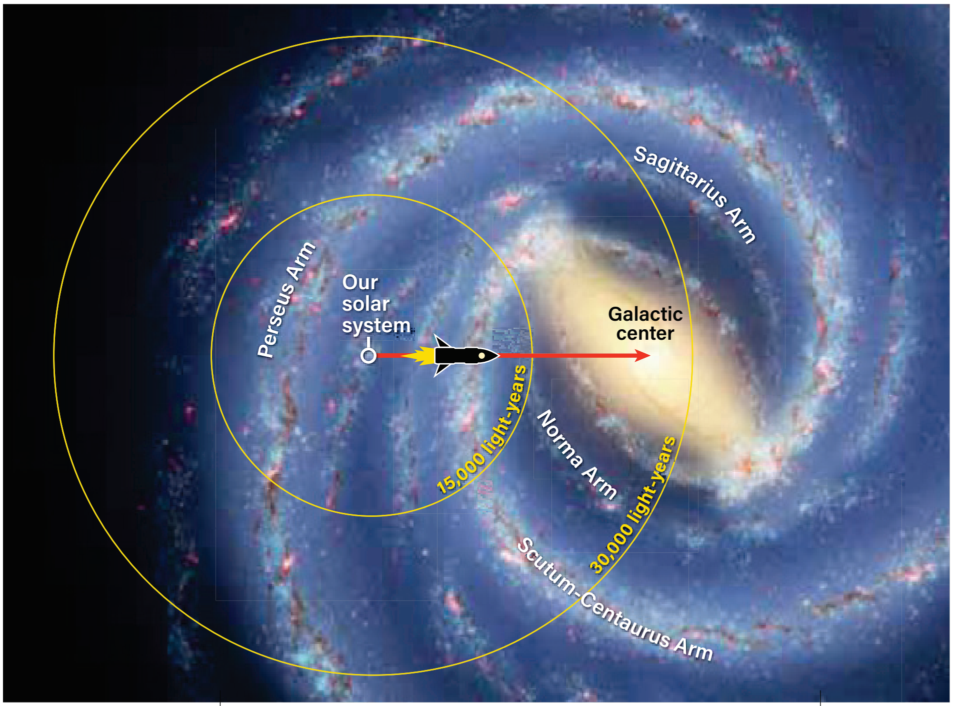


If a traveler could reach 99 percent the speed of light by accelerating at 32.2 ft/s^2 (9.8 m/s^2), they would experience the trip from Earth to the center of the Milky Way in about 20 years. *ASTRONOMY:* ROEN KELLY

Warp speed

Q | IF A CREWED SPACECRAFT COULD BE BUILT TO TRAVEL AT OR NEAR THE SPEED OF LIGHT, HOW LONG WOULD IT TAKE TO ACHIEVE THAT SPEED WITHOUT CRUSHING THE HUMAN OCCUPANTS?

Lawrence Schwab
Phoenix, Arizona

A | Despite what science fiction may suggest, humanity will never be able to travel at the speed of light. That said, we could theoretically get close. To cause the fewest problems for our human occupants, it would best to maintain the acceleration our body is familiar with: Earth's gravitational pull. At the surface of our planet, that is 32.2 feet/second^2 (9.8 meters/second^2). Accelerating at that rate, from the perspective of the traveler it would take 2.65 years to reach 99 percent the speed of light.

To better appreciate the result, consider that such a traveler wants to reach the center of the Milky Way. That's nearly 30,000 light-years distant. For half that distance, they'll want to accelerate at 32.2 ft/s^2 (9.8 m/s^2) and then decelerate by that same amount for the remaining half of the journey. At that acceleration, it would take the traveler around 20 years to get there — 40 years for a round trip.

But some weird things happen to time when moving close to the speed of light.

While only a few decades have passed for the traveler, significantly more time will have passed on Earth. Let's assume the impossible: The traveler manages to travel at the speed of light the entire way. In this case, nearly 30,000 years will have passed on Earth by the time they reach the center of the galaxy. For the round-trip journey, 60,000 years will have gone by at the end from Earth's perspective.

Needless to say, the traveler's friends at the time of departure would no longer be around when they return. This difference in observed time, or time dilation, is a consequence of Einstein's special relativity and illustrates his famous twin paradox.

Stuart L. Shapiro
Professor of Physics and Astronomy,
University of Illinois, Urbana-Champaign, Illinois

Q | CAN ISOLATED BLACK HOLES ACCOUNT FOR DARK MATTER?

Rick Pinson
Long Beach, California

A | Astronomers estimate about 100 million black holes wander the Milky Way. Since black holes emit no light, we rely on indirect methods to infer their presence. The first method is to search for a black hole's gravitational influence on nearby objects, such as stars.

Scientists believe that the Milky Way, like most galaxies, is surrounded by a dark matter halo (blue), as depicted in this artist's concept. ESO/L. CALÇADA

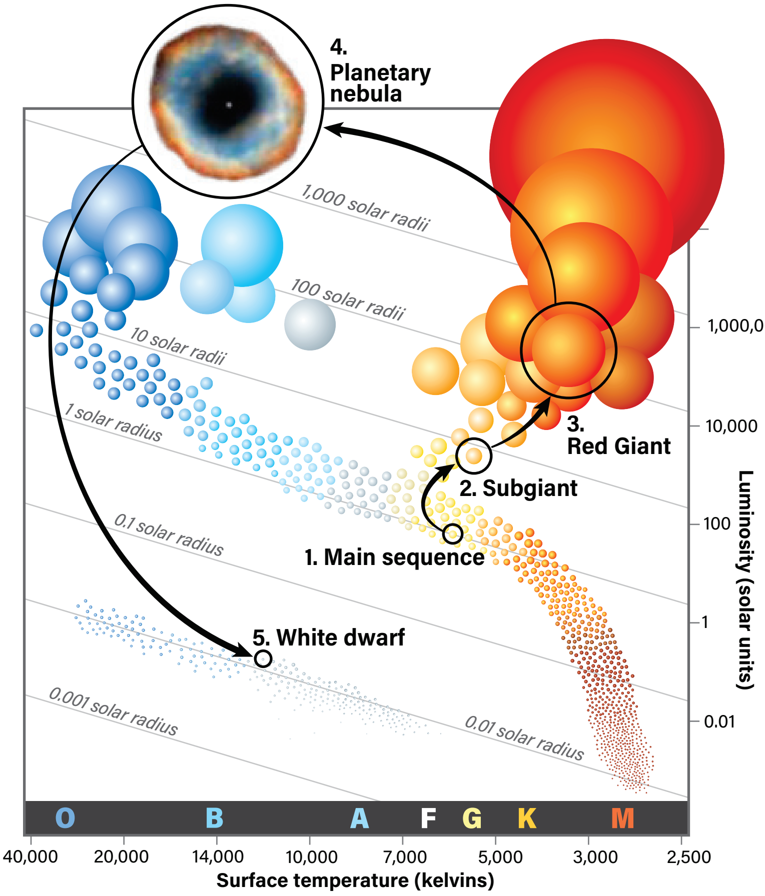
The second is to observe an accretion disk around a feeding black hole. Both methods, however, require one or more stars to reside near the black hole. Therefore, it's no surprise that scientists know of only about 20 black holes in the Milky Way — all of which are in binary systems, hence why we could find them. That does leave a lot of potentially unaccounted-for black holes in our galaxy.

Surrounding the disk of a galaxy is the stellar halo, a spherical population of stars and clusters. While the Milky Way's halo extends more than 300,000 light-years, it also sports a halo of dark matter (as do nearly all known galaxies) that may extend even further. Because stars located in the halo are typically older, researchers have indeed wondered if unseen black holes — along with other faint objects like neutron stars, white dwarfs, and planets — in the halo could account for a galaxy's dark matter. Collectively, these faint, compact objects are known as MAssive Compact Halo Objects, or MACHOs for short.

But based on observations of MACHOs, astronomers think these objects likely only make up 20 percent of the expected amount of dark matter in the Milky Way's halo. That leaves another 80 percent of dark matter present in our galaxy that cannot be made up of black holes.

Caitlyn Buongiorno
Associate Editor

THE HERTZSPRUNG-RUSSELL DIAGRAM



The Hertzsprung-Russell (HR) diagram acts as a map for stellar evolution. If astronomers know a star's temperature and luminosity, they can determine its evolutionary stage. Likewise, they can map the path the Sun will take (illustrated above) once it leaves the main sequence. *ASTRONOMY*: ROEN KELLY

Q | WILL THE SUN'S EXPANSION INTO A RED GIANT BE GRADUAL OR EXPLOSIVE?

John Haley
Huntsville, Alabama

A | Stars use pressure created by nuclear fusion to combat gravity and stay "alive." More accurately, this balance allows stars to stay in what is called hydrostatic equilibrium. Stars in the prime of their lives, fusing hydrogen into helium in their core, are in the main sequence. Stars like the Sun will spend approximately 80 percent of their lives in this phase. But each star has a limited supply of fuel, and it is estimated that in about 5 billion years, our Sun will cease hydrogen fusion and enter its red giant phase.

That's the simple story. This transition from the main sequence to red giant is actually quite gradual, even by astronomical standards.

In 5 billion years, once the Sun uses most of the hydrogen in its core, the pressure holding back gravity falls out of equilibrium. At this point, our star will enter what is known as the subgiant phase. Internally, the Sun's core will contract, which in turn will increase its temperature, igniting some more hydrogen fusion in a thin shell around the core. The layers outside the solar core will expand and, as a result, cool down. This expansion is gradual and takes about a billion years.

From there, the Sun will officially enter its red giant phase. The Sun's radius will keep growing and its temperature will decrease slightly. The energy emitted by the Sun, however, will increase enormously. Inside the Sun, the core will keep collapsing since there will be no source of energy; additionally, because fusion is occurring in the shell outside the core, the core gets heavier, causing it to collapse further. As that happens, the core's temperature increases.

This phase will last for about half a billion years. The red giant phase ends when the Sun's core gets hot enough (about 100 million kelvins) to support the fusion of helium into carbon. Once that threshold is met, the Sun will shrink again as it enters this final stage of its nuclear fusion life.

Sarbani Basu
William K. Lanman Jr. Professor of Astronomy, Department of Astronomy, Yale University, New Haven, Connecticut

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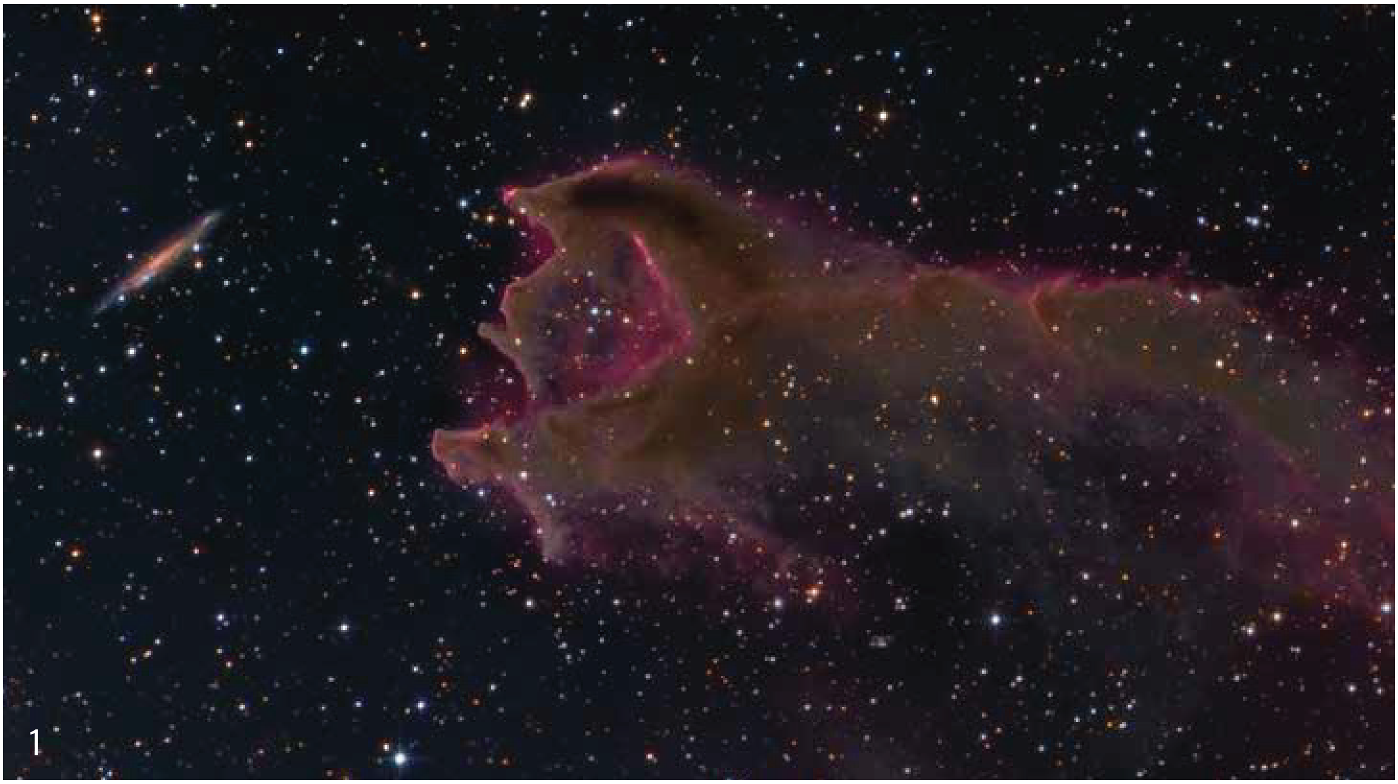
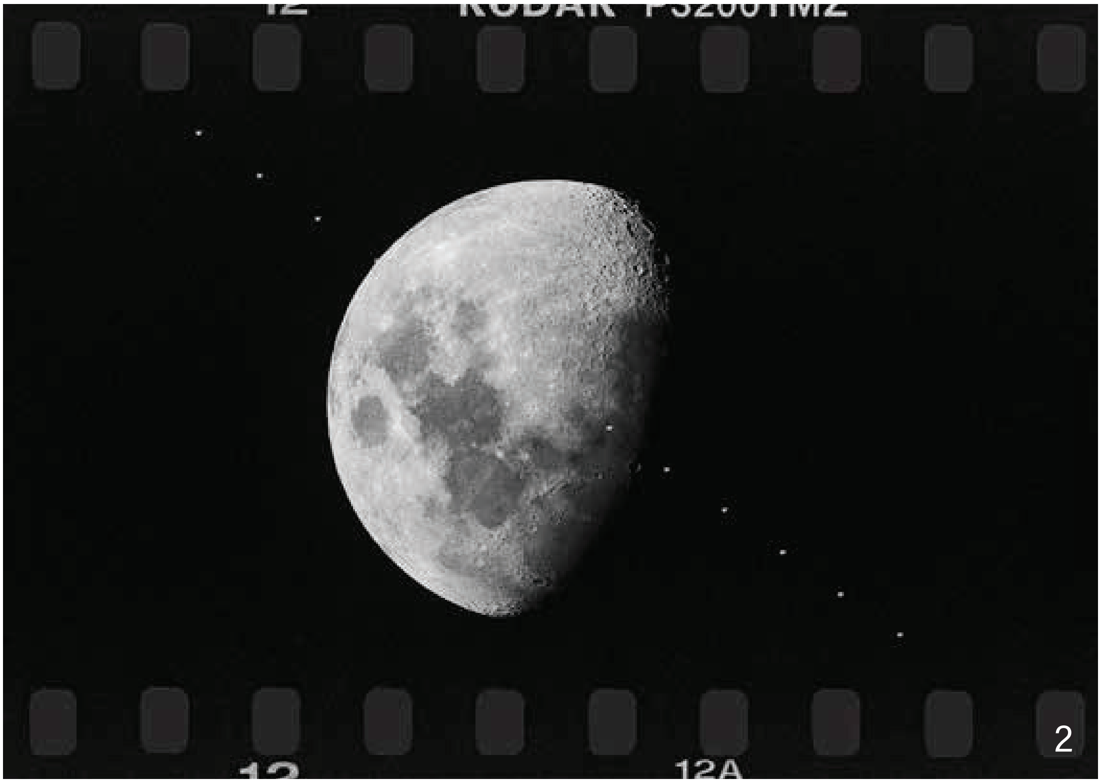
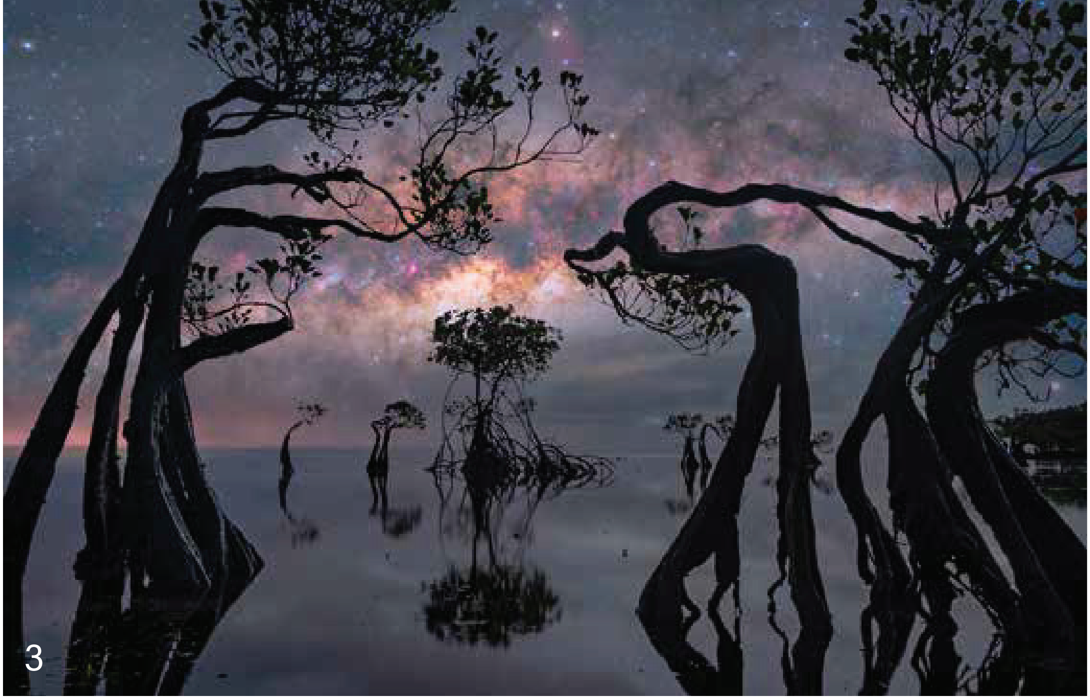
Cosmic portraits

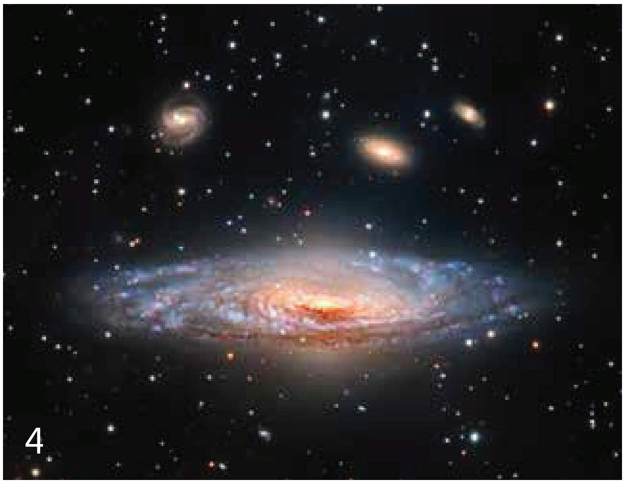


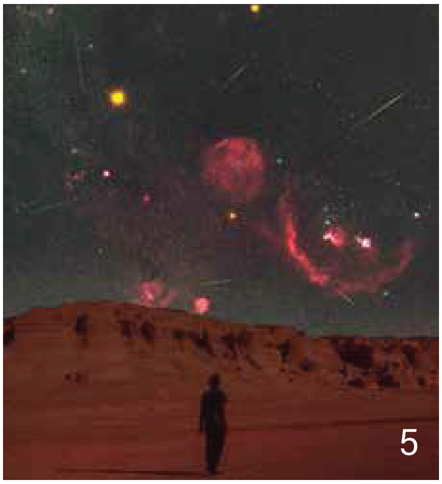
1. BA-DUM… BA-DUM… Cometary globule CG4 appears ready to devour the galaxy ESO 257–19 in this $H\alpha$LRGB image comprising five hours of exposure taken with a 24-inch scope. However, while CG4 lies roughly 1,300 light-years away in Puppis, the galaxy is about 100,000 times more distant. **▪ *Kfir Simon***

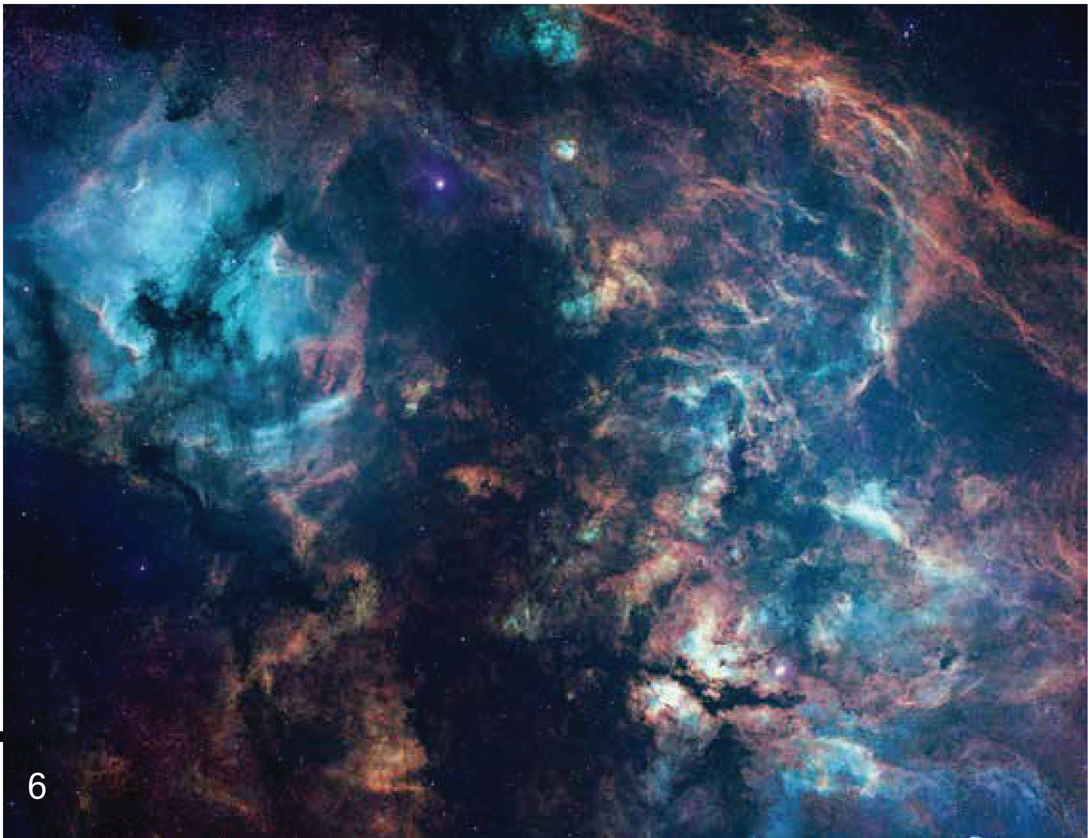
2. CAUGHT ON FILM This unique sequence of the International Space Station transiting the Moon was taken entirely on 35mm film. The photographer used a Nikon F5 — the last film SLR used in space by NASA — mounted on an 8-inch scope. The result is a composite of thirteen 1/500-second exposures on Kodak T-Max P3200 film. **▪ *Jason De Freitas***











3. DANCING IN THE DARK
The mangrove trees on the Indonesian island of Sumba are called "dancing trees" for their lithe contortions. In this image, the sky behind them comprises twenty 10-second exposures at ISO 12800 with a 24mm lens at f/2.8. To capture the waterscape, the photographer focus-stacked two 480-second exposures at ISO 800. • ***Vikas Chander***

4. AN ILLUSORY ENTOURAGE
NGC 7331 lies about 50 million light-years away in Pegasus; the smaller members of its group appear to buzz around it but are in fact background galaxies. For this shot, the imager took 21 hours of LRGB data with a 17-inch scope. • ***Bernard Miller***

5. DESERT HUNTER
Orion looms over the Egyptian desert, punctuated by its bright emission nebulae. The photographer captured the landscape first, lit by the Moon. After it set, he imaged the sky with eighty 120-second exposures using a Sony A7 III DSLR modified for Hα and a 35mm lens at f/2.8 and ISO 1250. • ***Wael Omar***

6. NEBULOUS CYGNUS
This wide-field view spans the North America Nebula (NGC 7000, upper left) across the Sadr Region to the Crescent Nebula (NGC 6888, lower right). The imager captured it with a 135mm lens at f/4 on a CCD camera and five hours of exposure in the Hubble palette. • ***Oleg Bouevitch***

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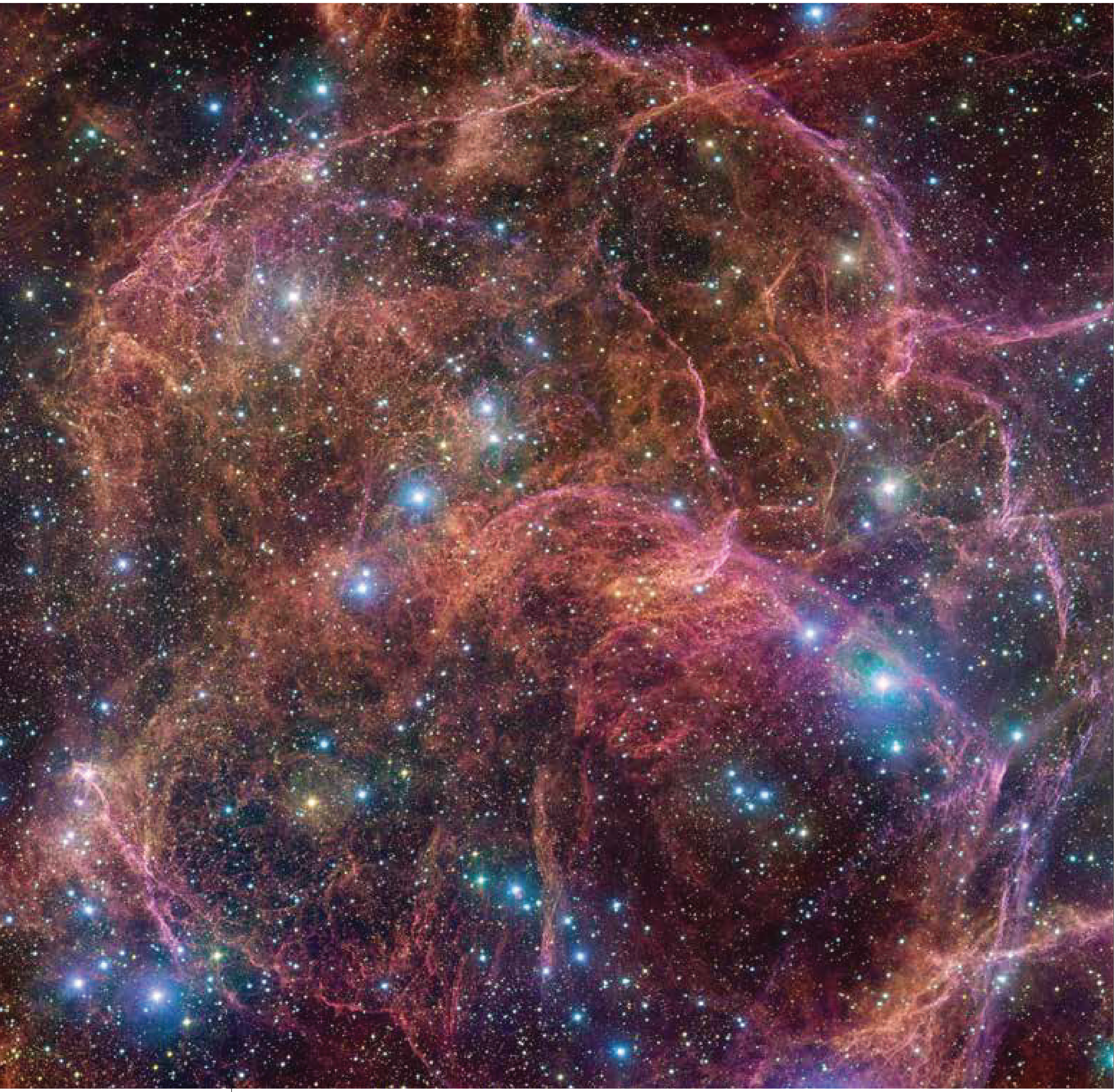

A SUPERNOVA SETS SAIL

The stars at night seem eternal. Our ancestors certainly felt a similar sense of stability — at least until one fateful night some 11,000 years ago. Anyone looking skyward then would have been frightened to see a steadily shining star grow a million times brighter within days and dominate the constellation we now know as Vela the Sails. Astronomers today understand that star was anything but stable. The massive sun's core had collapsed, triggering a shock wave that tore the rest of the star apart. We see that debris today as the Vela supernova remnant, an expanding cloud that spans 100 light-years and covers 8° of sky. (This image shows only a small part of the vast nebula.) ESO/VPHAS+ TEAM

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